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PROGRESS IN RADIATION SHIELDING RESEARCH FOR PROTECTIVE SHELTERS

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by
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OBJECT OF TASK

To improve existing knowledge on gamma and neutron shielding properties of shelters.

ABSTRACT

The present status of radiation shielding technology is reviewed, with particular emphasis on protection against radiation resulting from nuclear weapons explosions. The exposition, oriented toward an audience of civil engineers, describes the basic concepts and presents brief descriptions of important research work carried out in various institutions in this country during the past decade. An extensive list of source material is provided.

FOREWORD

This note is essentially the text of a speech made by the author before a meeting of the Construction Division, American Society of Civil Engineers, at its Reno, Nevada, convention, on 23 June 1960. The speech has been expanded by including more detailed explanation and providing extensive references.

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INTRODUCTION

Until a few years ago, the subject of radiation shielding was, like all nuclear technology, considered a study in applied physics. Today it is a subject of such importance and practical usefulness that engineers find it necessary to become acquainted with it and adopt it as part of their own respective engineering disciplines. It is still a subject which is expressed in the language of the nuclear scientist, which uses terms unfamiliar to most engineers, and which indiscriminately mixes English and metric units, both "practical" and "absolute." At present therefore, advances in knowledge of radiation shielding are occurring primarily by means of the combined efforts of both nuclear physicists and engineers.

There are many who believe that the practical, applied aspects of nuclear technology are sufficiently broad and distinctive to require the establishment of a new type of engineer, called a "nuclear engineer." There are other leaders in our technological society who believe just as firmly that no such new breed of engineer is warranted, but that each of the older engineering disciplines must take unto itself those problems created by the atomic age. I personally have dodged this question; aside from calling myself a physicist, I am registered as a professional engineer and have carefully put myself down on the registration form as both a "nuclear" and a "civil" engineer.

Whatever may be the point of view of the individual civil engineer, there is no doubt that in applying nuclear technology to many structures, the very walls and other structural elements may have special requirements. Many times such walls have a primary function of providing radiation shielding. Even elements having other primary functions may demand analysis as radiation shields to satisfy additional functional criteria. In such cases the structural engineer must have some appreciation of the radiation shielding problem and its solutions.

My own particular interest in this borderline field between engineering and physics is in the design and construction of atomic bomb shelters. Until recently the primary concern of those developing such shelters was the protection against blast. I venture to say that almost all the work of civil engineers in evolving bomb shelter design concepts has been from this point of view. Yet the radiation aspect is of great importance, and in many cases of such a paramount importance that it must be considered in establishing the design criteria for such a structure. I shall, therefore, slant this discussion heavily toward the atomic bomb radiation problem. Most of the principles involved, however, are of widespread validity and will serve for almost any problem related to radiation shielding, whether the radiation comes from nuclear reactors, atomic bombs, nuclear accelerators, radioisotopes, x-ray machines, or other radiation sources.

BASIC CONCEPTS

In trying to present a picture of some of the research work going on in the field of radiation shielding, I think it desirable to review briefly the basic aspects of the subject. This may be elementary for some of you, but it is necessary for others who are not familiar with the special nomenclature, symbols, and concepts.

Let us refer to Figure 1. As this figure shows, the types of radiation generally hazardous to us here on earth are called alpha, beta and gamma rays, and neutrons. The first three can originate from radioactive atoms of matter, but neutrons come generally as a result of a nuclear reaction - such as fission of very heavy atoms into lighter atoms. In such a fission process, which is the basis of nuclear energy (whether uncontrolled as in a bomb, or controlled as in a power reactor), there is an immediate output of gamma and neutron radiation from the fissioning atoms. The residual fragments of the fission process are themselves radioactive, and for a considerable time after the fission they emit gamma rays and beta rays. Unsplit atoms which are scattered about as a result of an explosion may also emit alpha rays.

Alpha rays are the nuclei of helium atoms, and are so ineffective in penetrating the skin that they are not a hazard from outside. They are dangerous only if material giving off alpha particles has entered into the body. The same thing is true of beta particles, which are simply high speed electrons, although electrons may also cause surface burns on the skin. In both cases, shielding against such particles is simple. Any reasonable thickness of material will suffice. It is desirable, of course, to keep any appreciable amount of the radioactive material giving off such particles out of the air we breathe or the food we eat. Alpha and beta particles are thus generally termed "internal" hazards.

Gamma rays and neutrons are another matter. They are highly penetrating, and are just as much a hazard if the source material is outside the body as within. In fact, since the source material of gamma rays and neutrons are normally outside of the body in much greater strength than we expect to find them inside, they are usually termed simply an "external" hazard. The problem of shielding, then, is to prevent gamma rays, or neutrons, or both, from entering the human body from some source material which emits them.

Gamma rays are essentially the same as high energy x-rays, and as such they are generally more penetrating than lower energy x-rays. What is said about gamma rays will, in principle, apply to x-rays, however. Thus the principles I describe for gamma rays will cover to a certain extent the problem of shielding of hospital x-ray rooms, nuclear accelerators (which put out many x-rays), and commercial fluoroscopes. These gamma rays are so-called "electromagnetic" rays, and are similar to light waves and radio waves - differing in their wave-length. Such rays come in individual units, or packets, called "photons," almost like particles. The ease of shielding these rays depends upon the energy content of each photon packet. Gamma rays may be produced by nuclear reactors during and after operation, directly by atomic bombs (including so-called hydrogen bombs), and by the ashes or fission products from the bombs. We normally call the latter "fallout." They may also be emitted by certain radioactive materials such as cobalt-60, radium, and many others. (High energy x-rays machines may be considered as included in this list also.)

Neutrons are produced almost directly from the fission reaction, or from certain other induced nuclear reactions. From a practical point of view, we are concerned with their production either from atomic bomb explosions, reactor operations, or accelerator operations. They do not result from radioactive fallout emission. Neutrons are basic constituents of matter and are quite penetrating. They are considered particles, rather than waves. (I must admit that particles and waves of such microscopic dimensions have very similar properties, but this need not concern us here.)

I will try to use familiar units as much as possible, but this is not entirely possible. One unit with which it is necessary to be familiar is the "electron-volt." It is equal to 1.18×10^{-19} foot-pounds, which is, as you can see, quite a small number. Nevertheless it is quite an appropriate unit to use, for neutrons may be of concern to us if they have energies of this low an order of magnitude or even lower. The unit is often abbreviated "ev."

Multiples of this unit are used: 1 Kev is 1000 ev; 1 Mev is 1000 Kev, or 1,000,000 ev. Gamma ray photons which are penetrating enough to be of concern usually are higher than, say, 50 Kev, or 0.05 Mev, in energy. Neutrons may be of concern with energies from many Mev right down to 1/40 ev, at which energy they are in thermal equilibrium with the atoms of matter they traverse. In such case they are called "thermal" neutrons.

Another unit to remember is the "roentgen." This unit measures the "exposure dose," i.e., the response of an idealized instrument placed in a gamma radiation beam; and it is related to the ionization produced in air at that spot. The rate of production in air of this ionization by the beam of radiation is commonly called the "dose-rate," measured in terms of roentgens per hour or some similar unit. This unit is fairly large, and smaller units, such as the milliroentgen, are useful. A very similar unit - which for our purposes may be considered quantitatively almost equivalent - is the "rad." If a substance such as human body tissue receives 100 ergs of energy per gram at a certain point, then it has received a dose of 1 rad at that point. The roentgen thus measures the radiation field; the rad measures the amount of energy absorbed by matter, such as human tissue, at any point in the field. To orient our thinking on this matter, it might be appropriate to mention that a human being receiving an exposure dose of about 500 roentgen of gamma radiation over his whole body has only about a 50-50 chance to survive for 30 days or longer.

Let me now review some basic shielding concepts. I should point out in advance that what I say will apply to gamma ray shielding a little more accurately than neutron shielding, since special complications sometimes exist for neutrons. However, there is a general similarity.

Consider now the situation depicted in Figure 2. If we have a narrow parallel beam of radiation photons or particles, each having the same energy, passing through a slab of material of thickness x, the attenuation, represented by the ratio of the dose rate on the exit side divided by the dose rate measured at the incident side, is given by the formula:

$$\frac{D}{D_o} = e^{-\mu x}$$

where x is fairly small, for example, not over a few inches of concrete for gamma rays or energetic neutrons. In the case of gamma rays, μ ("mu") is known as the "linear absorption coefficient." In the case of neutrons, the same concept and the same formula apply, but for some reason - probably because many of the early neutron physicists didn't recognize its essential similarity to the older x-ray concepts - the absorption coefficient in the case of neutrons is often called the "macroscopic cross-section," and is designated by various symbols, as μ ("mu"), σ ("sigma"), or Σ (capital "sigma").

We may notice here that some of the photons or particles are absorbed in the material, but others are knocked aside by collisions with atoms of the shielding material. In either case, they have been removed from the narrow incident beam and, if we assume no further interaction with air or other matter beyond the shield, are not observed by the detector instrument beyond the shield.

Figure 3 gives a graphical plot of the attenuation ratio given for the foregoing formula. You see the exponential shape on a linear plot, and will note particularly that on a semi-log plot it is a straight line. This is especially important and is generally characteristic of the great majority of practical shielding situations, and occasionally even under very complex conditions. It can also be noted that increasing the thickness of the shield by a certain fixed amount, called the "half-thickness," will attenuate the radiation by a factor of one-half. The same concept can be used to set up a standard distance for any particular attenuation ratio desired. For example, it is often desirable to know the material thickness to provide a reduction in dose-rate by ten-fold, and thus the "ten-folding length" is a concept often used. It can be shown also that the negative slope of the line equals the absorption coefficient, μ, divided by log e.

Figure 4 gives a slightly less elementary situation which is nonetheless readily solvable. We see that for a point source, or a source concentrated in a small volume (to be more realistic), the attenuation occurs not only by reason of the material shielding, but also by reason of the tendency of the radiations to spread out as they proceed from the source. If at one unit distance from the source the dose-rate is D_1, the dose-rate at point 2 would be:

$$D_2 = \frac{D_1}{R_2^{\,2}}$$

(Precisely, to keep the equation dimensionally correct, we should write:

$$D_2 = D_1 \left(\frac{1 \text{ unit}}{R_1}\right)^2$$

.) This relationship is known as the "inverse square law." If the shield were not present the dose-rate at point 3 would be:

$$D_3 = \frac{D_1}{R_3^{\,2}}$$

Thus, with no shield present, the relative dose-rates at points 3 and 2 would be:

$$\frac{D_3}{D_2} = \left(\frac{R_2}{R_3}\right)^2$$

With a shield of thickness x interposed, the ratio of dose-rates becomes:

$$\frac{D_3}{D_2} = \left(\frac{R_2}{R_3}\right)^2 e^{-\mu x}$$

It is quite customary, when examining the shield effectiveness in such a situation, to bring the R^2 terms on the other side of the equation, so that we compare and take the ratio, not of the dose-rates, but of the dose-rates multiplied by the square of each distance from the point-source. Thus:

$$\frac{D_3 \cdot R_3^{\,2}}{D_2 \cdot R_2^{\,2}} = e^{-\mu x}$$

A plot of such a ratio then becomes a straight line on a semi-log scale, as before.

Let us now pass on to another complication, still involving thin slabs. Figure 5 illustrates a situation known as "parallel broad-beam" geometry." We note that the situation is different from "narrow-beam geometry," previously discussed, in one important respect. As in the narrow-beam case, part of the radiation which would hit the detector instrument is scattered into another direction; however, the part that is scattered out of the beam is compensated for by "in-scattering" of radiation which would not have hit the detector had no shield been present. As before, a part of the dose measurement reduction is due to radiation absorption. The other important source of reduction is a single essential fact: when radiation is scattered it loses energy. Thus, even though the radiation knocked out of the path to the detector is compensated for, numberwise, by radiation scattered into it, the in-scattered radiation has lower energy. Dose is closely related to energy, and thus the scattering, though not entirely effective in lowering the dose, is partially effective. The formula for attenuation by the shield in this case can be written as:

$$\frac{D}{D_o} = e^{-\mu' x}$$

This has the same form as the attenuation equation for the narrow-beam case depicted in Figure 2. μ' is however less than μ, which is used for the narrow-beam case. This means that the attenuation for the broad parallel-beam case is less than for a narrow-beam case. See Figure 6.

It might be noted here that this use of a μ' is not quite as fundamental as the use of μ to characterize the narrow-beam case, and in specific situations it is usually determined experimentally. The use of this approach for the broad-beam case is at present somewhat out of favor in comparison with newer approaches to be described shortly.

Let me emphasize that the formulas presented up to this point are reasonably valid only for rather thin shields - say, on the order of less than half a foot of concrete for high energy gamma rays or neutrons. This is because I have assumed thus far that the radiation photons or particles, if scattered at all, are scattered only once. It is apparent however that if the shield is so thick as to provide a very high chance of their being scattered once before passing through the shield, there is also a good chance of some of them being scattered more than once. For very thick shields, or for low energy photons or particles, this so-called "multiple scattering" effect is too important to be ignored. On the other hand, simple universal formulas are not easily come by for predicting this effect. Figure 7 gives, as an example, a semi-log plot for attenuation of parallel broad-beam radiation perpendicularly incident on slab shields of varying thicknesses of concrete, based on actual experiments. At the beginning of the curve, the thin shield case is valid and the slope of the line corresponds to what was designated above as μ'. As the shield is made thicker, the curve appears to seek a new slope, which corresponds to what we might call an "effective attenuation coefficient." Corresponding to this is an effective half-thickness, which as explained above, indicates the thickness of additional shielding material which would reduce the radiation by a factor of two. (The straight line tail of the curve is not universally valid behavior, but is closely approximated in many practical situations.)

In Figure 8, there are listed some typical values of half-thicknesses under various conditions for shields. It is well for all engineers who are involved in nuclear projects of one sort or another to obtain some quantitative appreciation of these figures. No trends are presented, but simply a wide variety of important situations. Explanation of some of the terms will follow in the remainder of this presentation.

REQUIREMENT FOR SHIELDING RESEARCH

Until about a decade ago, theory and experiment had not brought us much further than this. Even here there were gaps. Basic narrow-beam absorption coefficients for gamma rays had been determined experimentally with a fair degree of accuracy, and they were in reasonably good agreement with theoretical calculations. Equivalent information for neutrons was rather sketchy, and neutron shielding estimates were based on calculations which combined semi-empirical theory with previous experimental experience. It was common, however to find that after shields for nuclear facilities were designed, constructed, and put into actual use, they were appreciably over-designed or under-designed. In many cases, additional shielding had to be added to nuclear facilities after they were presumably finished.

About a decade ago, a number of factors stimulated renewed research in this field. As nuclear facilities showed promise of being more practical, and less experimental in nature, a closer look at facility economics was taken. Precise nuclear shielding design thus has become more desirable in order to avoid wasting money. Also, the use of reactors in propulsion vehicles, such as in submarines and in aircraft, indicated the need to shave weight and space requirements as close as possible. Thirdly, increasing awareness of the need for a major civil defense shelter program in view of the widespread radiation hazard posed by more powerful atomic weapons has made it essential to refine our engineering capabilities of analyzing and designing structures with a view to radiation protection.

Let me say at this point, that it has been this third factor which has been of most concern to me. Although my direct concern is with military structures, yet out military problems in this regard are very similar to the civil defense interests. The military and the Office of Civil and Defense Mobilization have collaborated closely on such matters.

As a consequence of my own special interest, the larger part of the research work I am going to review for you is work related to the atomic defense program, and my discussion cannot be considered an exhaustive survey of all shielding research which has occurred in the last decade or that is going on today. Let me assure you, on the other hand, that most of the research work I will cover has applications much more general than just radiation-resistant bomb shelters.

TECHNIQUES

In my mind the most outstanding theoretical achievement of the past decade in the general field of radiation attenuation was published in 1951 by L. V. Spencer and U. Fano (Reference 1 and 2) of the National Bureau of Standards. This was a completely analytic approach to the problem of predicting attenuation of radiation in an infinite, homogeneous medium, with particular emphasis on situations in which large amounts of material exist between the source and the detector of the radiation.

This approach is known as the "method of moments." Whereas the problem of radiation attenuation can be set up mathematically, the resulting equations have thus far proven impossible to solve directly for the resulting attenuation function. On the other hand, Spencer and Fano turned the equation into a series of equations for the "moments" of the attenuation function, which were solvable. A knowledge of the moments of the attenuation, or shielding, function can lead us to a knowledge of the attenuation function itself. (Civil engineers can readily understand what the "moments of a function" are, since they correspond directly to familiar mechanics concepts: the zero moment in the area under the attenuation function curve; the first moment is the statical moment of this area about the y-axis; the second moment is the moment of inertia of this area about the y-axis; and so on.)

This technique was exploited by H. Goldstein and J. E. Wilkins of Nuclear Development Associates, Inc., for monoenergetic gamma rays, using a variety of source configurations, a wide spread of source photon energies, a great number of different shielding media, and a wide range of shielding thicknesses. The variety of source configurations studied include those shown in Figure 9. The results obtained were "cranked out" through an elaborate computer program. They have been published in Goldstein and Wilkins' report (Reference 3) in the form of tables and graphs. In use, this information is expressed in the form of a so-called "build-up factor."

Figure 10 shows how the build-up factor works. If the attenuation were to be expressed by the usual narrow-beam elementary expression, $e^{-\mu x}$, we would get the lower line shown. An accurate analysis by the moment method gives a curve resembling the upper line. We can define B as a correction factor, which depends on μx, to be applied to the lower curve to give the correct curve. Thus, the correct results are given by $B \cdot e^{-\mu x}$, where $B = B(\mu x)$. Thus, for a relatively simple source configuration, if we know what the material is, and if we know the initial energy of the radiation from the source, we can estimate the dose at any reasonable distance from the source.

It is appropriate to remark that this technique has been tried for neutrons as well as gamma rays. It is much more difficult for neutrons, however. For one thing, there are differences in the detailed mechanics of neutron energy loss which make accurate analytical predictions more difficult than for the gamma-ray case. Also, the "cross-sections," or coefficients for absorption and scattering for neutrons, are not regular, simple, and analytically expressible as in the case of gamma rays, but are extremely erratic - undergoing wide variations with respect to changes in neutron energy and the type of shielding material. In fact, there is still a major effort going on, under the sponsorship of the Atomic Energy Commission, the Department of Defense, and other agencies, to improve our knowledge of these coefficients. For these and other reasons, analytical approaches to the neutron penetration problem have not been as adequate as for gamma rays, and there is still research work to be done in this area.

I might bring to your attention, in case you haven't already noticed, that the geometric configuration of the attenuating material, assumed for calculation of the build-up factors by the moment method, is not that of a flat slab which we have been discussing but extends infinitely in all directions (see Figure 9). Actually, this latter case is not as impractical as it might seem to be. Under many circumstances, the difference between results in the two cases is not as great as might be imagined - that is to say, the important part of the shielding is that part of space between the source and the detector, and the other portions, which constitute the difference between a slab shield and a completely infinite medium, often only exert a secondary influence. (There are, on the other hand, situations of substantial difference between the two approaches for which the results are not very comparable. A great deal of understanding in shielding technology is required to exercise proper judgment in this respect.)

There are a wide, really infinite, number of physical situations in which the distribution of the source of the radiation and the configuration of the shield are not suited to accurate analysis by any existing, strictly analytical method. One way of solving such problems is by use of a mathematical technique known as the "Monte Carlo" technique. Those of you who have been sampling the gambling facilities of Reno might be interested in learning how to put your gambling instinct to a useful purpose. First we should realize that the so-called "absorption coefficient" or "cross-section" expresses directly the probability that something will happen to a particle of radiation as it traverses a unit distance in the shielding material. This can be divided into portions, corresponding to the various things which may happen - complete absorption, scattering without loss of energy, or scattering with loss of energy. Once these coefficients are known, we can play a little gambling game on paper, with the help of some device, of the nature of a roulette wheel a pair of dice, or some other more appropriate means of insuring randomness of specific occurrences but with predetermined likelihoods. The system is this: Consider a single gamma ray photon of a certain energy incident initially on the shield. Follow its life history as follows: Let us see what might happen in the first centimeter of its travel. By means of the gambling device, set to the relative probabilities of no-action versus some sort of reaction, let an arbitrary decision be reached as to whether the photon continues in its path or something happens to it. Let the gambling device decide what process, if any, will occur. Then follow the photon along successive path increments until it either is absorbed, or is reflected back from the face of the shield, or passes finally through the shield. As you can see, for a thick shield, the chances of its passing through are not large. If we do this 10,000 times, however, we may find - say - 10 getting through. Then we are reasonably sure that the shielding effectiveness is about 10/10,000 or 1/1,000.

This sounds very tedious, and indeed it is, but by use of a large electronic computer set up to do this automatically, with the appropriate kind of gambling system incorporated in it, this process can be carried out many, many times without undue human labor. As one example of the use of this technique I might mention the work of Zerby (Reference 4), who tackled the problem of shield penetration by gamma rays with two complicating factors: the shield was made up of laminations of more than one material, and the radiation incident on the shield was at various slant incidences rather than being normal to the shield surface. Other instances of the use of the Monte Carlo technique will be cited below.

From this point on, I will review recent and current radiation shielding research by outlining, in turn, the work of various organizations which have been concerned to an appreciable extent with this problem.

RESEARCH AT ORNL

The first I might mention briefly is the work at the Oak Ridge National Laboratory of the reactor shielding group under the leadership of E. P. Blizard. His work has been devoted almost entirely to the problem of reactor shielding, especially for reactors involved in the nuclear aircraft propulsion program. Other groups have been engaged in similar work, such as those at General Electric's Knolls Laboratory, Schenectady, and at Convair, Fort Worth. Much of their work is rather specifically oriented to aircraft problems, and some of it is undisclosed by reasons of military or AEC secrecy requirements. I won't go further into such work, therefore. It must be mentioned nevertheless that Blizard has published an excellent review of the general subject which summarized the state of progress in shielding technology as of 1955 (Reference 5).

It might be appropriate at this point to mention that there are some other excellent treatises wholly or partially on this subject which have been published (References 6 through 13). None of them are oriented specifically to atomic defense shielding problems, although much of their information is applicable thereto. A few lesser known but excellent reference works, including information specifically on atomic bomb shielding technology, have been put out in very recent years or are presently in preparation, primarily by or under the auspices of the military departments or the OCDM. I will list some of them at the conclusion of my presentation.

Also at the Oak Ridge National Laboratory a group in the Health Physics Division, G. S. Hurst, R. H. Ritchie, J. A. Auxier, and others, have been working on the problem of correlating the radiation effects on the people of Hiroshima and Nagasaki with the actual radiation doses to which they were exposed (Reference 14). In doing this they have studied the radiation attenuation of Japanese-type houses (see Figures 11 and 12 for results). They have also made experimental measurements at Nevada atomic bomb tests to study how air scattering affects the direction of propagation of neutrons and gamma rays as they proceed from the bomb burst point to the structures in question.

This same group has also, because of their general interest in Civil Defense, made measurements of the radiation attenuation for American as well as Japanese homes. By using radioactive materials placed around homes in Oak Ridge to simulate fallout, they actually determined fairly accurately the shelter potential of these homes for fallout protection. They found, for example, that if houses are built on the sides of hills in such a way as to expose a basement wall on the down-hill side, the basement loses much of its effectiveness as a shelter - the protection factor changes from about 1/30 for a good basement to about 1/10. (References 15 and 16).

RESEARCH AT NBS

Some of the most outstanding work in this field, especially on the more basic (and therefore the more generally applicable) side has been at the Bureau of Standards. I have already mentioned the theoretical work of Spencer and Fano on gamma ray penetration by the "moments" method.

Also you will recollect my discussion of the work for gamma ray shielding done by Goldstein and Wilkins of the NDA, using the Spencer-Fano method. Figure 13 shows another situation analyzed theoretically in similar manner by Spencer and Lamkin at the Bureau of Standards, for concrete (Reference 17). Here the parallel broad-beam radiation attenuation is considered for an oblique angle of incidence of the radiation on the source plane. Results of dose reduction have been calculated for various values of the angle, θ_o, and at various distances, z, from the source plane.

The Spencer-Lamkin results are quite applicable to the situation shown in Figure 14. Here we see something approximating the configuration of a large underground shelter; and the dose in the shelter can be given approximately by entering the Spencer-Lamkin tables for the distance, z, from the source plane.

Since the results are tabulated for various angles of incidence of the radiation, the situation wherein the radiation comes in from all angles can be readily handled by obtaining the dose resulting from radiation at each specific angle, and then integrating over all incidence directions. These research workers have done this for water as well as concrete (Reference 18), since both these materials are quite useful for shielding purposes. Separate calculations were made and tabulated for 26 different source energies, all the way from very energetic photons at 10.22 Mev down to very weak ones at .043 Mev.

It is thus possible to handle situations not only involving a combination of various directions of incoming photons, but also a mixture of energies. Thus if we can predict what the various photon energies and directions in relative numbers would be at the shield surface from an atomic explosion (or from any other source), we can make a rather good estimate of the shielding effectiveness of an underground shelter of reasonably standard construction. Spencer and Lamkin have done this for certain sources having mixed gamma rays (Reference 19).

Some excellent experimental work on the problem of attenuation of broad beams of gamma rays of various energies with slant incidence through concrete walls or slabs has been done by Kirn, Kennedy, and Wyckoff of the Bureau of Standards (Reference 20). Some typical results of their measurements are shown in Figure 15. You will note how the attenuation varies with angle of incidence. Obviously the more slanted the angle of incidence, the more material the radiation has to go through for a given slab thickness. However, it does not behave exactly as if it were going through material of thickness equal to the slant thickness, especially for heavy walls. An analysis of these data has led me to some simple rules-of-thumb for attenuation of slant incidence gamma rays through concrete (Reference 21). Refer to Figure 16:

(1) If the angle with the normal (angle "a") is less than about 35°, the usual method of replacing the situation on the left side by the situation on the right side for computational purposes, is approximately valid. Above 35°, this elementary approach becomes increasingly invalid.

(2) For rather thin concrete walls (less than about 1/2 foot), the elementary approach may err, but gives results on the safe side. The opposite is true for appreciably greater thicknesses, and carefully obtained analytical or experimental data must be used.

Unfortunately, simple rules-of-thumb are not always so easily obtained for less simple situations.

M. J. Berger is another Bureau of Standards scientist who has been active in radiation shielding calculations. He and Lamkin have shown how one can, by judicious simplification and idealization, attack practical problems (Reference 22). Examples of their approach are given in Figure 17. You will see how each of the practical situations considered can be analyzed by use of a schematization which lends itself to one or another of the theoretical approaches.

As an illustration of how the schematization works, consider the middle problem, of the house covered with fallout on the roof, and a person at the ground level where the dot is located. The dose received here is very close to that received in the infinite, homogeneous medium (similar to the roof material) at a point below the source plane at a distance equal to the roof thickness. The finiteness of the roof area modifies the situation in that only radiation coming within the dotted lines affects the dose measurement at the ground line, and therefore the computation in the schematized infinite, homogeneous medium must be modified to accept dose contributions coming only within similar angular limits.

The third situation depicted is sometimes called the "foxhole" situation. This is very important to the military, as you may imagine. It is also of significance in determining the effectiveness of basements in providing protection against fallout. The radiation which is computed in this case is that being back-scattered into the hole by the atmosphere. This contribution to the dose is known as "sky-shine."

It has more recently been shown by Eisenhauer (Reference 23) and Spencer (Reference 24) that in the foxhole situation there is also an appreciable contribution caused by radiation passing directly or almost directly from the source through the "lip" of the foxhole.

Berger and some of his co-workers have been particularly concerned about the general problem of "back-scattering," of which "sky-shine" is one particular aspect. Closely related is the "reflection" of radiation from solid or liquid media, called "albedo." For example, Berger and Doggett (Reference 25) did some rough Monte Carlo calculations of the back-scattering of gamma radiation from concrete slabs. The results indicated for example, that in the situations depicted in Figure 17, an additional contribution of about 15% to the dose can be expected by reason of this effect, which is not accounted for in the basic calculation. Berger and Raso (the latter is now with Technical Operations, Incorporated, but was at that time at the Army Chemical Center, Edgewood, Md.) have recently completed more extensive Monte Carlo calculations to determine the totally reflected amount of radiation when initial parallel broad-beam monoenergetic gamma rays of various energies, incident at various angles, strike plane-surfaced, infinitely thick slabs of various materials, such as water, concrete, and iron (Reference 26). Plans are now being made under the sponsorship of the Naval Civil Engineering Laboratory, which I represent, to have these same gentlemen do some more extensive back-scattering work, which will tell just how much gamma radiation is scattered in each direction. This will assist NCEL in some of our analyses of the "duct" problem, which I will describe later.

Work has also been done at the Bureau of Standards to determine the proportion of the various gamma ray photon energies emitted by fall-out particles. This is known as "fission-product decay energy spectra." After all, in order to determine the penetration of the radiation, one has to know its various energy components. Based on tables of abundances and activities of nuclides resulting from bomb fission compiled by Bolles and Ballou (Reference 27) of the U. S. Naval Radiological Defense Laboratory, two Bureau of Standards scientists, A. T. Nelms and J. W. Cooper (Reference 28) analyzed the spectra and calculated a total output as a function of energy content of the photons. Their results are shown on Figure 18, for the distribution of photons by energy content at about a half-hour after the fission has occurred. It should be pointed out that others have made similar compilations.

Note that these results compare favorably with experimental information provided by Zobel and Love (Reference 29). The source of the slight discrepancy at about 3.5 Mev has not been determined, to my knowledge. Its influence is minor however.

Berger and Titus have been doing some work in determining how a marked change in density of material across an interface separating two homogeneous semi-infinite regions will create a variation in the results computed for the completely infinite homogeneous situation by Goldstein and Wilkins (Reference 3). This is of great interest since in most practical cases, sources and detectors are positioned rather close to the interface between earth and atmosphere; and correct results cannot always result from assuming that all space is filled with either earth or air, which assumption would make the "moments" method applicable. This work was done in a variety of ways, both theoretical (by Monte Carlo Methods) and experimental (Reference 30, 31). One of the most interesting was the use of a volume consisting of a heavy steel slab on one side of an interface and with steelwool on the other. See Figure 19.

Caswell and co-workers at NBS have been concerned with reported discrepancies between theory and experiment in regard to shielding effectiveness of water for neutrons (Reference 32). He has partially resolved these discrepancies, and has ascribed them largely to difficulties inherent in making good theoretical calculations for neutron attenuation.

This does not exhaust the contributions of the Bureau of Standards, but we simply can't list all of them. Some further reference will be made below to certain other interesting work in which NBS personnel are involved.

RESEARCH AT NRDL

The U. S. Naval Radiological Defense Laboratory has been working on shielding problems for some years, primarily for ships. Because civil engineers are not primarily concerned with this type of structure, I don't think there is any point in covering the subject in detail. The work is being carried on at present under the leadership of W. E. Kreger, by N. E. Scofield, B. W. Shumway, and others, and is primarily of an experimental character. Generally, they have found that the theoretical tools available to them are adequate for predicting the radiation attenuation capabilities of ships; however, there are some particular complications which cause discrepancies under some conditions. A ship of course is somewhat like a large building, in that it is cut up by floors and vertical walls into many compartments.

One can see from Figure 20 how these compartmenting walls tend to channel any radiation coming from above. On the other hand, the scattering effect in the attenuation process by the floors tend to spread the radiation. The roles of the walls and floors are reversed for radiation coming from the side. The degree to which these two processes cancel is something Kreger and his group are studying, both in actual ships and in idealized steel models (Reference 33).

Kreger's group is also doing some "back-scattering," or "albedo" experimentation. They are primarily interested in iron, but expect also to work on soil and concrete (Reference 33).

Since most of this shielding work is not of immediate importance to civil engineers, I will forego further description of this group's contributions to the general shielding technology. It is worth adding, however, that many other scientists at NRDL have done work which bears at least indirectly on the atomic bomb protection problem. They have exhaustively studied the characteristics of bomb radiation, both the initial radiation and the fallout radiation; they have studied the problem of fallout particle distribution from an atomic explosion; they have contributed toward many facets of civil defense and shelter design.

RESEARCH AT NRL

I might also mention the Naval Research Laboratory as a contributor to this technology. Much of the interest in shielding at that Laboratory has been related to reactor shielding, either for its own experimental reactor or for the Navy's nuclear propulsion program. Some of its contributions have been related to atomic defense areas, however, and there have been some sufficiently basic to be widely applicable. An early but outstanding effort on the problem of "albedo," or back-scattering, by slabs was done by R. B. Theus and L. A. Beach of NRL for 6-Mev gamma rays incident at various angles on iron. This was done by the Monte Carlo technique, and over 100,000 individual photon histories were traced to give the results, which are very complete (Reference 34).

Some year ago, in order to give the Navy a better comprehension of the shielding capabilities of its structures, NRL undertook to do some shielding studies of two kinds: the first was related to the effectiveness of a standard Navy concrete barracks building in attenuating the fallout radiation hazard; the second was an attempt, based on rather crude assumptions, to predict the attenuation of the Navy underground shelter types for the more immediate atomic bomb radiation. This work was done by C. A. Malich and L. A. Beach (Reference 35). In regard to the first problem, Figure 21 illustrates some of the interesting results. Note how the varied sources of the radiation produce different dose levels at different stories in the structure. Particularly, one should notice the greater effectiveness of windowless structures in fallout radiation protection.

The NRL study of the problem of underground shelter protection against initial bomb radiation provided results illustrated in Figure 22. The various contributions are separately grouped, as well as the total. Note that the gamma radiation caused by neutron interaction with the air is most important.

These same two subjects have been more exhaustively studied in recent years, but the results have not been changed significantly since Malich and Beach's report was published. For example, we might note an independent estimate of attenuation for the Navy underground shelters, made by J. C. LeDoux at the Navy Civil Engineering Laboratory (Reference 36). See Figure 23. The curves which represent the attenuation of the so-called "nitrogen gammas" are closely consistent with the corresponding curves in Figure 22 called "gammas from air."

RESEARCH AT NCEL, ETC., ON DUCTS

We have lately been interested at NCEL in the so-called "duct" problem. This may be considered to include the "entranceway" problem. The problem is this: No matter how thick the shielding may be of a habitable shelter, there must always be holes in the shield. These holes may be as large as a shelter entranceway, or they may be as small as a utility duct. And as an intermediate size we might consider ventilation passageways. The problem of building a radiation resistant shelter, once the walls and roof are made thick enough, is similar to that of building a photographic dark-room which will keep out the light and at the same time admit air and people. The solution is qualitatively simple - do just as you would for a dark-room, make the passageways or ducts with one or more bends in them. Figure 24 shows a typical solution.

Some work, both experimental and theoretical, has been done on how much radiation gets through such ducts, both straight and with turns in them. Rough experience has indicated that every turn of approximately 90 degrees, through which the radiation is scattered in order to pass down the duct, provides an attenuation in the average entranceway by a factor on the order of 1/10. (This is only a rough rule-of-thumb.) Analytical approaches of a semi-empirical nature have been derived by several workers, such as Barcus, Simon and Clifford (References 37, 38). These are in theory applicable to both gamma rays and neutrons. To get good numerical answers from these equations good information as to scattering or "albedo" by the walls is necessary. Since our present knowledge of such "albedo" is somewhat imperfect, we are not yet in position to check the theory. As indicated above, a program to improve the "albedo" data is being made by NCEL in conjunction with the Bureau of Standards.

Further than this, there are some additional correction factors which need to be applied to make good agreement between theory and experiment in the "duct" problem. Eisenhauer, of the Bureau of Standards, (Reference 23) has investigated experimentally an effect in square ducts which he calls the "corner effect."

Figure 25 shows how, for square ducts, the effect can be significant. With a source at the mouth of the two-legged duct, some of the radiation can penetrate the inner corner edge, which therefore increases the amount of radiation which can scatter from the farther wall. Also some of the radiation which scatters from the near wall may penetrate the corner edge in its path to the detector. Finally the corner itself might provide a scattering effect into the detector for photons which otherwise might not hit the detector. Other effects of possible significance remain to be investigated. LeDoux and I are examining this duct question at present; and Eisenhauer at the Bureau of Standards is continuing his work. Also a certain amount of work is being done of an experimental nature at the Brookhaven National Laboratory, I understand (Reference 23). Likewise NCEL is sponsoring some work by C. W. Terrell, at Armour Research Foundation, who will investigate both neutron and gamma ray attenuation down straight ducts, two-legged ducts, and three-legged ducts of square cross-section, and of sizes from 1 foot square to 6 foot square in cross-section. The sources of radiation expected to be used will produce both monoenergetic and mixed energy beams of gamma rays and neutrons.

One experimental set-up which is planned at ARF is shown in Figure 26. Note the reactor which is at one end of the simulated entranceway. This entranceway will be made of movable concrete blocks or slabs, and the reactor emission can be used as is, or with modifications to provide either predominantly high energy neutrons, a standard fission spectrum, almost pure thermal neutrons, etc. Artificial radioactive sources can be used when the reactor is shut down and shielded; pure gamma rays can be obtained from a shut-down but unshielded reactor.

WORK AT BUREAU OF YARDS AND DOCKS

The Bureau of Yards and Docks, where I had duty before I came to NCEL, has taken great interest in and provided some of the support for the shielding programs I have outlined above. In addition, its personnel have made certain studies designed to put this technology on a basis that an engineer without extensive training in nuclear science can understand. For example, Figure 27 shows the results of some calculations that L. N. Saunders and I (Reference 21) undertook a few years ago. We had occasion to develop under simplified assumptions a graph which would indicate the attenuation for fallout radiation expected by the roof of an underground shelter of finite area. The results are as seen. The dotted line, for comparison purposes, shows a more recent curve of Spencer (Reference 24). This dotted curve is for equivalent weight of air rather than concrete, but shows close similarity up to about 18 inches of concrete thickness.

I think one of the most useful things that the Bureau of Yards and Docks has done was to make a compilation of the series of studies just mentioned into a publication called "Technical Studies in Atomic Defense Engineering" (Reference 21). These studies cover all phases of the subject of atomic bomb protection, including radiation shielding, but not limited to it. It includes not only work done by the Bureau of Yards and Docks, but also contributions from many other sources. This work is still in progress, and future additions to the compilation will undoubtedly be published.

OTHER RESEARCH

I have mentioned Technical Operations, Incorporated, previously in these discussions. This private research organization has been involved in this type of shielding research work in recent years, under the general direction of E. T. Clarke. One of the outstanding contributions to the technology made by this organization has been the development of a means for moving a highly radioactive source around an area by remote control to simulate a distributed field of fallout particles. This is done by looping a long plastic tube around the area, and through this tube pumping hydraulic fluid which pushes the radioactive source through at a predetermined rate. Figure 28 shows a simple line diagram of this apparatus. By this means, Clarke and his fellow workers have been able to study existing buildings of substantial size to determine their radiation shielding capability (Reference 39). Other agencies have copied the Tech/Ops technique for similar purposes. Such experiments are invaluable in providing a practical test of the adequacy of existing analytical techniques of shielding analysis. The ultimate aim of such research is to predict within a correctness factor of 1.5 what the shielding effectiveness of any structure is for a reasonably well known radiation source. This is considered an adequate goal for shielding specialists, and certainly is less than the safety factor of 2.0 which structural engineers ordinarily apply to their work.

Another military laboratory engaged in structural shielding research is the Chemical & Radiological Laboratory at the Army Chemical Center, Edgewood, Md. At this Laboratory, R. Rexroad, H. Tiller, H. Donnert, and others of the Nuclear Engineering Branch are carrying out experiments using a highly simplified but carefully constructed structure for checking calculations of shielding effectiveness (References 23, 40). This structure is a simple blockhouse, square in plan and having concrete walls of equal thickness all around. With various wall thicknesses and roof thickness, they have checked calculations of attenuation by placing radioactive sources, both distributed and concentrated, in various places on the roof and on the ground. Further experimentation is planned to include the effect of simple openings in the walls, to represent doors and windows. Dose measurements are to be made within the simplified structure at all key points. No results have been published as yet, but the experiments are expected to be a valuable link between idealized theory and the very practical experiments on real buildings discussed above.

Also at CRL, Tiller and others are making further studies on the "foxhole" problem (Reference 40). Donnert is doing work on the neutron albedo problem (References 23, 40).

CONCLUSION

I promised you that at the conclusion of my discussion I would provide a list of some of the important texts or handbook references in the field of atomic shelter shielding analysis or design. These are as follows:

Title	Author or Sponsor	Ref.
Effects of Nuclear Weapons	Dept. of Defense and Atomic Energy Commission	41
Studies in Atomic Defense Engineering, P-290 and P-290.1	Bureau of Yards and Docks	21
Report on Current Knowledge of Shielding from Nuclear Explosions	Spencer, L. V. and Hubbell, J. H. (Bureau of Standards)	42
Fallout Shelter Surveys: Guide for Architects and Engineers	Office of Civil and Defense Mobilization	43
OCDM Engineering Manual - Design and Review of Structures for Protection from Fallout Gamma Radiation	Office of Civil and Defense Mobilization	44
Structure Shielding Against Fallout from Nuclear Weapons (to be published as OCDM publication)	Spencer, L. V. (Bureau of Standards)	24

I wish in particular to point out the last on the list, which is as yet only in draft form. Dr. Spencer is doing an outstanding service in placing fallout radiation shielding technology on a basis which engineers can understand and utilize without having to become nuclear physicists. He has recognized its interest to civil engineers - I quote from the draft of his work: "The contents and organization of this monograph have been influenced by the fact that this may properly be considered a branch of either nuclear or civil engineering..."

This work will shortly be published under the auspices of the OCDM, and I hope that some members of the civil engineering profession will obtain it, study it, and become familiar with it.

Meanwhile, there is more research work to be done in the field of nuclear radiation shielding, both in the fundamentals and in the engineering applications. Data must be generated, collected, and presented in useful form. New practical rules-of-thumb can probably be devised. Revisions and new editions to all text books and reference works will be needed.

ACKNOWLEDGMENT

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Appreciation is expressed to the several agencies under whose sponsorship much of the original work reviewed herein was carried out for the permission to refer, summarize, or quote from the original works, published or unpublished. These include National Bureau of Standards, Defense Atomic Support Agency, Bureau of Yards and Docks, and Office of Civil and Defense Mobilization.

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Rays	Character	Some Common Sources	Approximate Shielding required
α–rays	helium nuclei	radium, plutonium	sheet of paper
β–rays	electrons	fission products	few millimeters of sheet metal
γ–rays (x–rays)	electromagnetic waves	fission, fission products, accelerators	one or more feet of concrete
neutrons	uncharged nuclear particles	fission, accelerators	one or more feet of concrete

Figure 1. Summary of radiation types

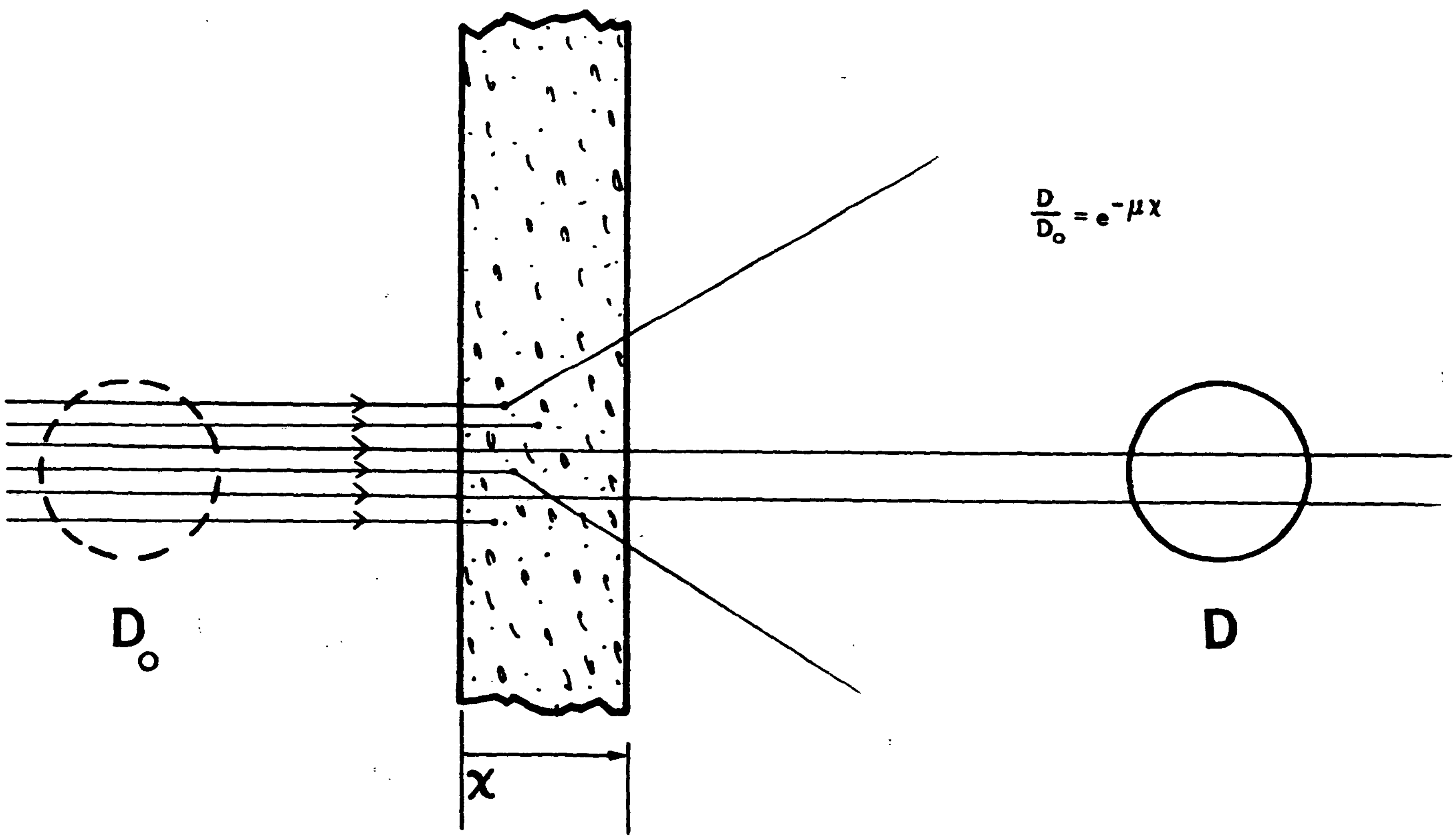


Figure 2. Narrow parallel beam, thin slab shielding

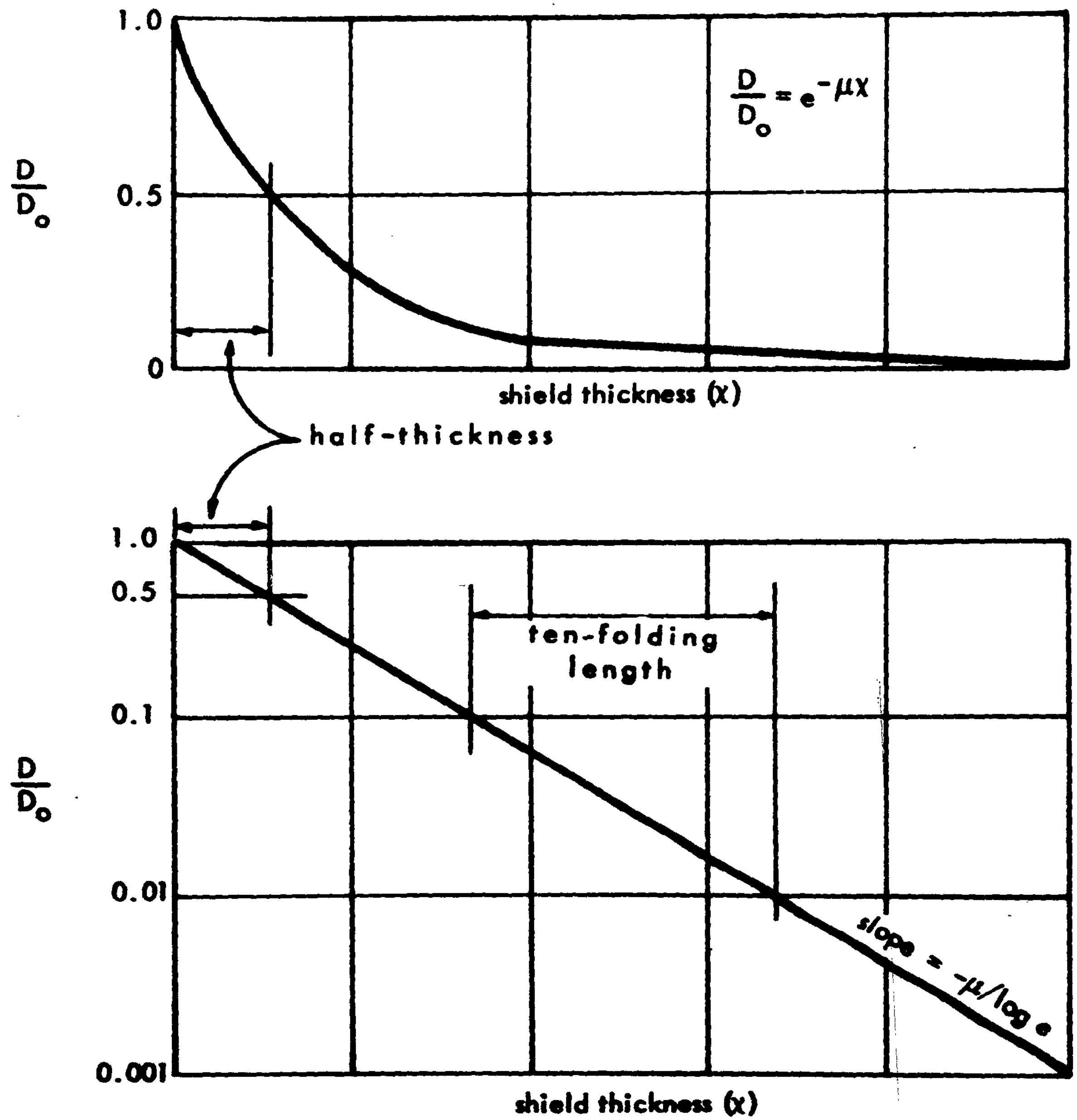


Figure 3. Elementary shielding formula, linear and semi-logarithmic graphs

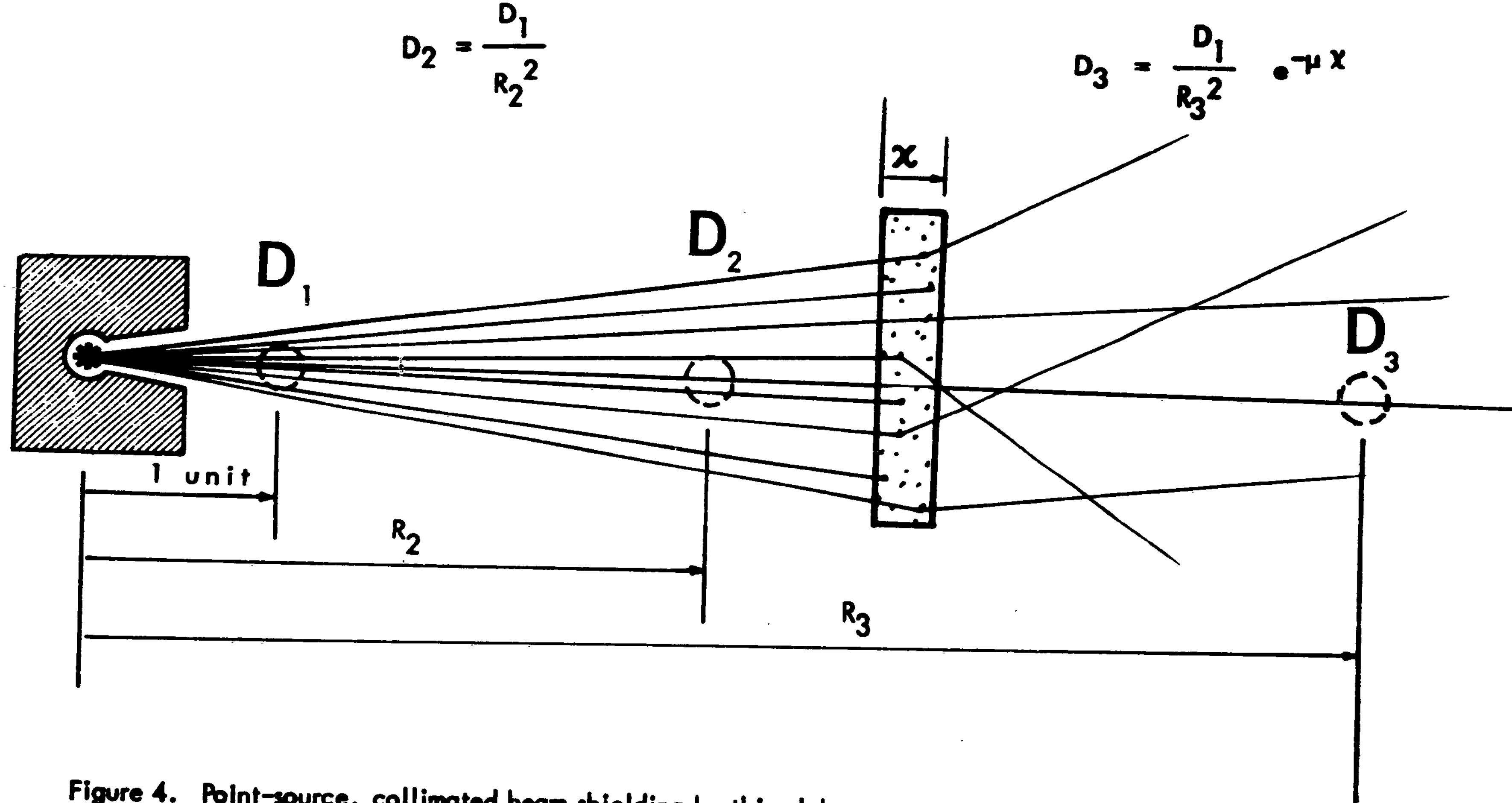


Figure 4. Point-source, collimated beam shielding by thin slab

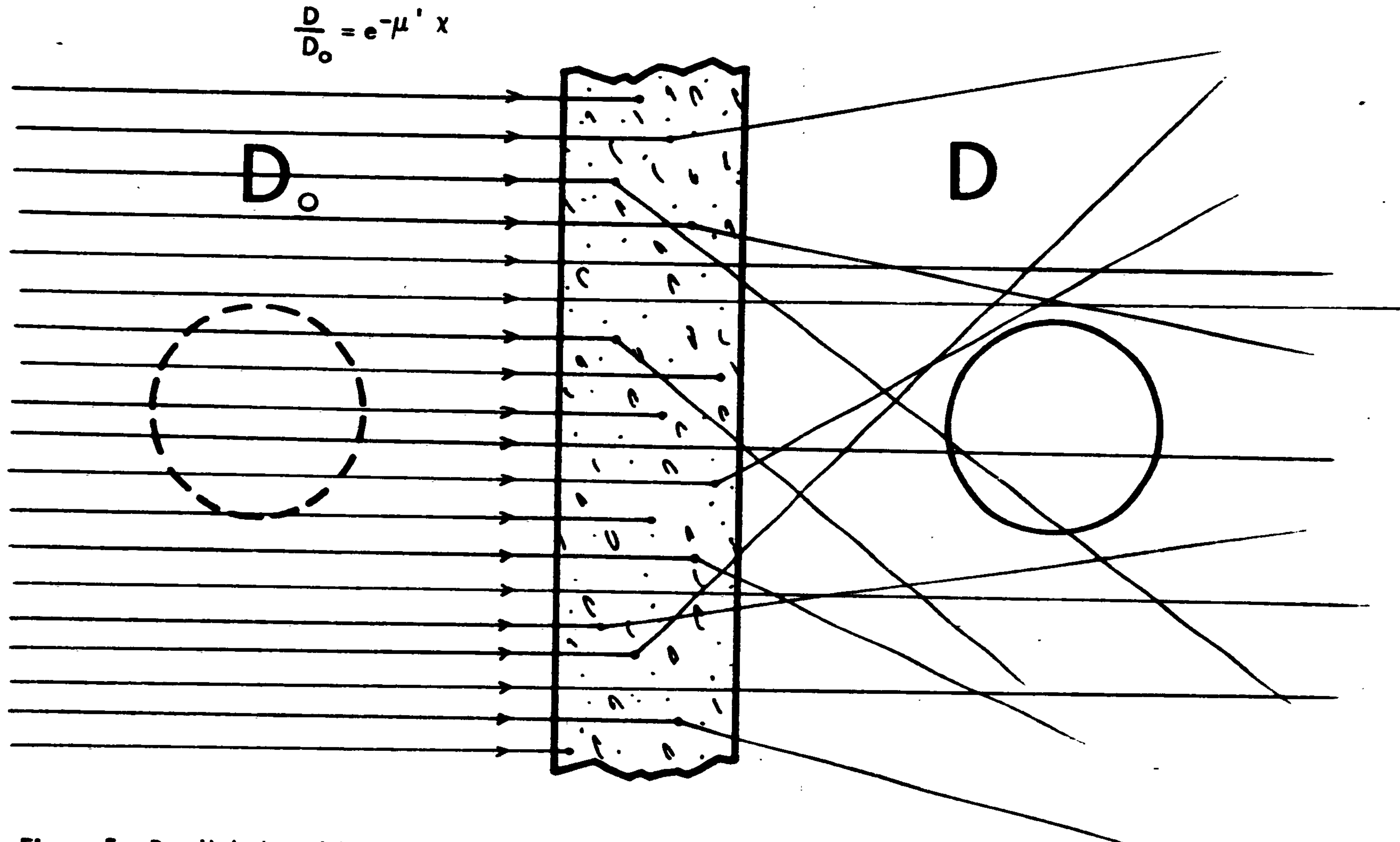


Figure 5. Parallel, broad-beam shielding by thin slabs

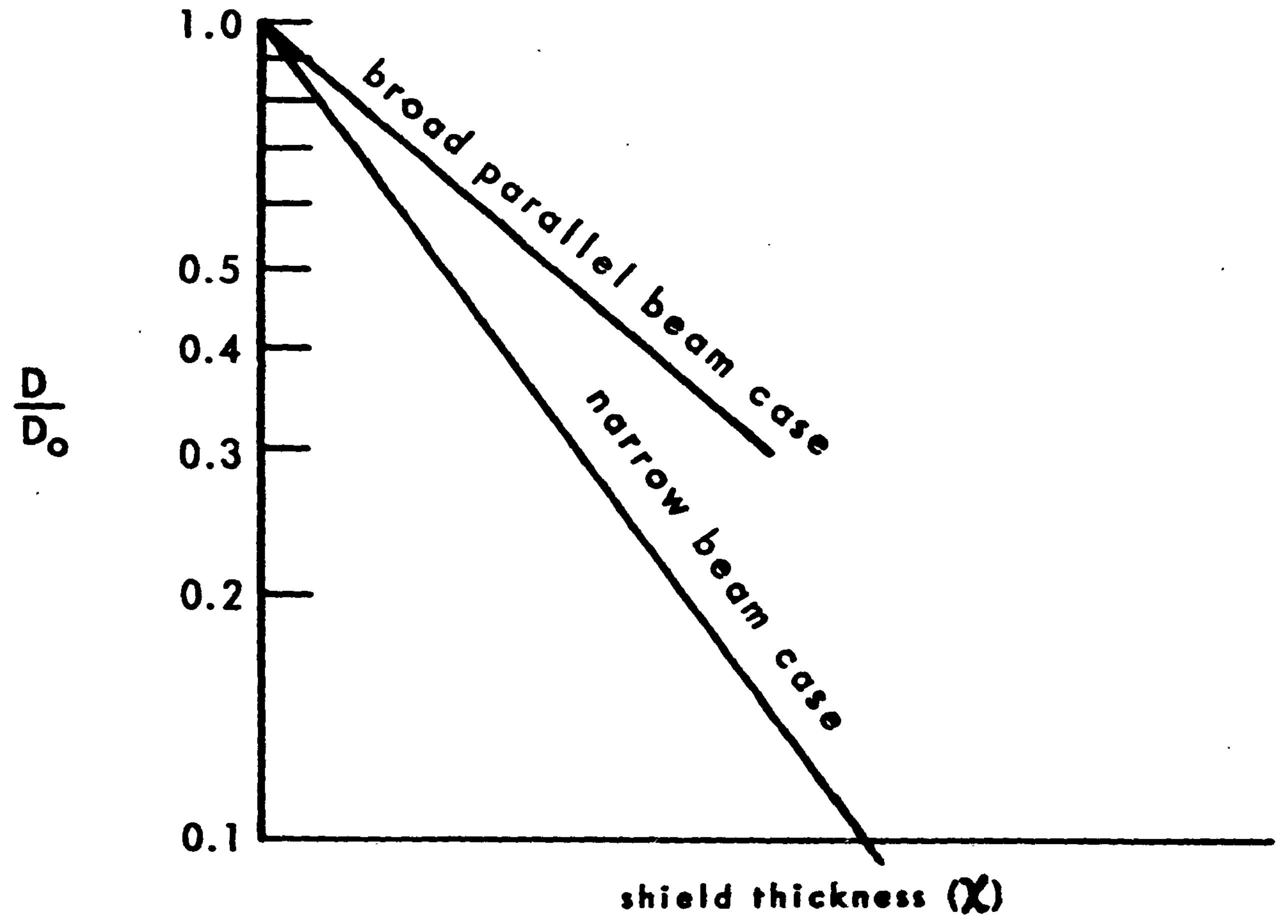


Figure 6. Comparison – narrow vs broad–beam attenuation in thin slab shields

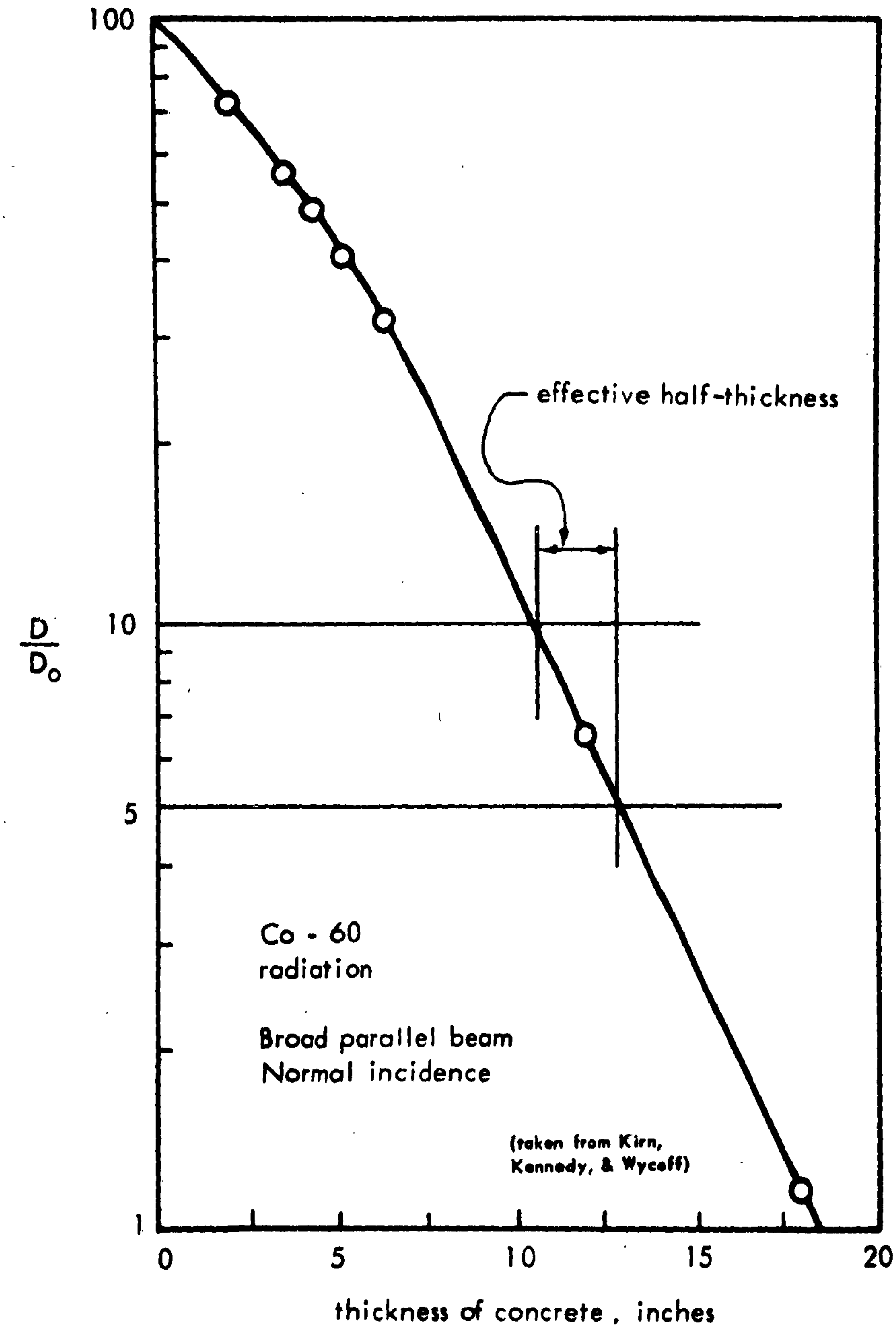


Figure 7. Broad, parallel-beam attenuation in thick slab shields of concrete – normal incidence

Radiation	Energy	Shield Material	Shield Configuration	Beam Geometry	Half Thickness Inches
Neutron	Thermal	Water	Slab	Point Isotropic	2.1
Neutron	14 Mev	Soil, 110 pcf 10% moisture	Slab	Broad Beam, Normal Incidence	6.0
Neutron	Thermal	Soil, 110 pcf 10% moisture	Slab	Broad Beam, Normal Incidence	5.6
Neutron	Fission spectrum	Concrete	Slab	Broad Beam, Normal Incidence	3.1
Gamma	6 Mev	Soil, 110 pcf	Slab	Broad Beam, Normal Incidence	8.3
Gamma	Fission Products	Soil, 110 pcf	Slab	Plane Isotropic	3.2
Gamma	1.25 Mev	Soil, 110 pcf	Infinite Medium	Point Isotropic	2.7
Gamma	4.0 Mev	Concrete	Slab	Broad Beam, Normal Incidence	5.7
Gamma	Fission	Concrete	Slab	Point Isotropic	2.2

Figure 8. Half-thickness of common materials under various conditions

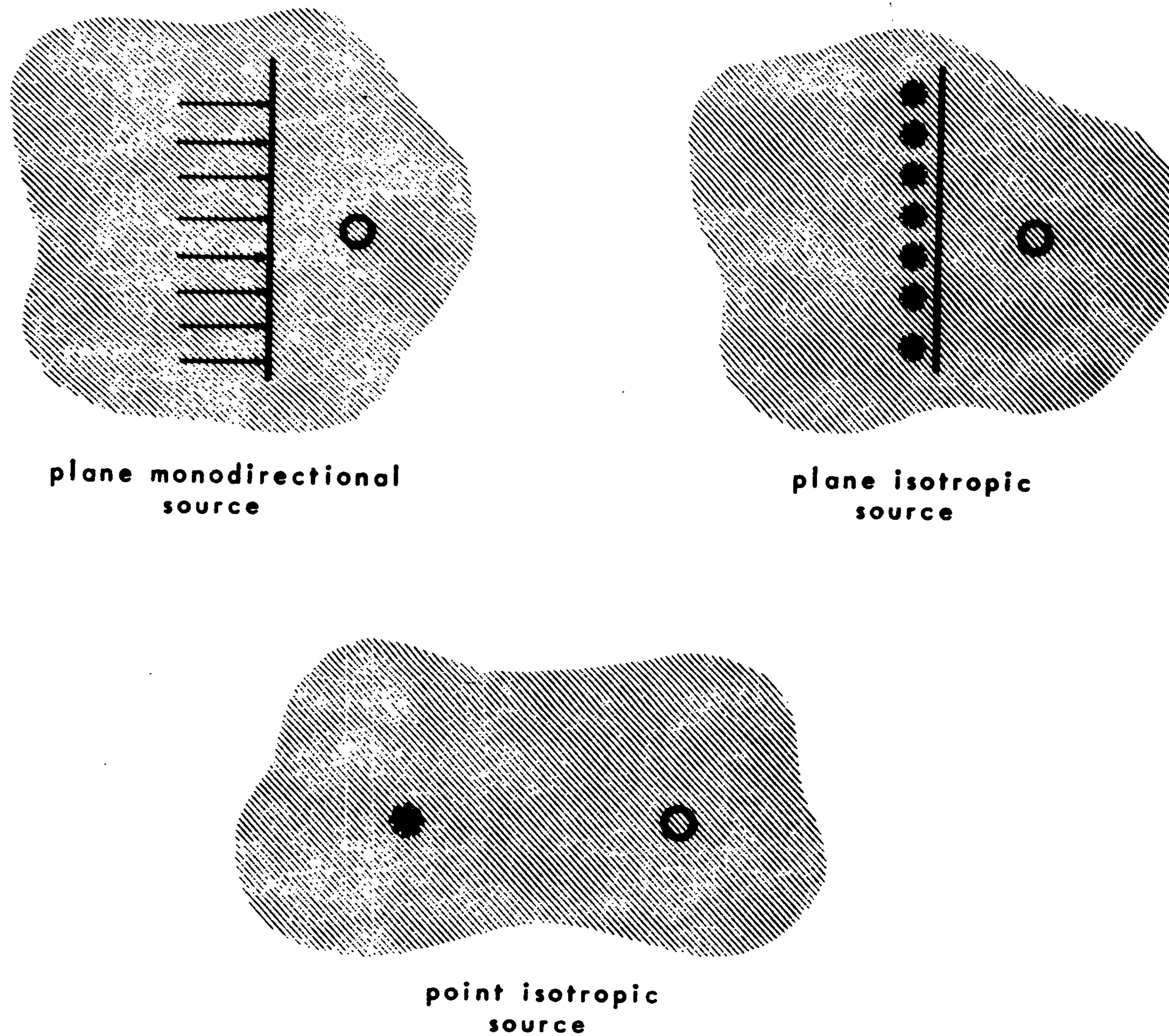


Figure 9. Source and detector buried in medium – various situations studied by moments method

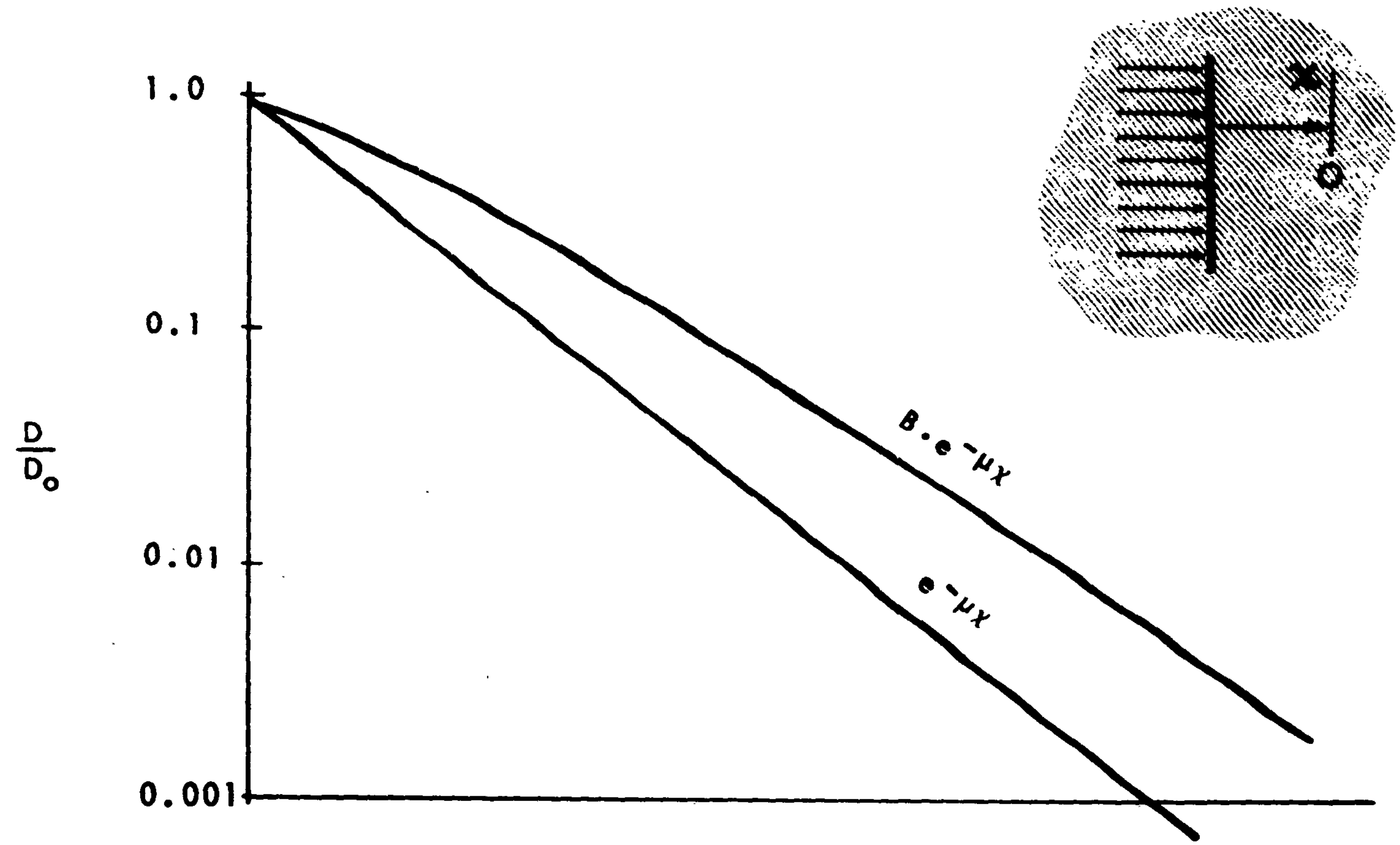


Figure 10. "Build-up" factor concept for parallel, broad-beam radiation

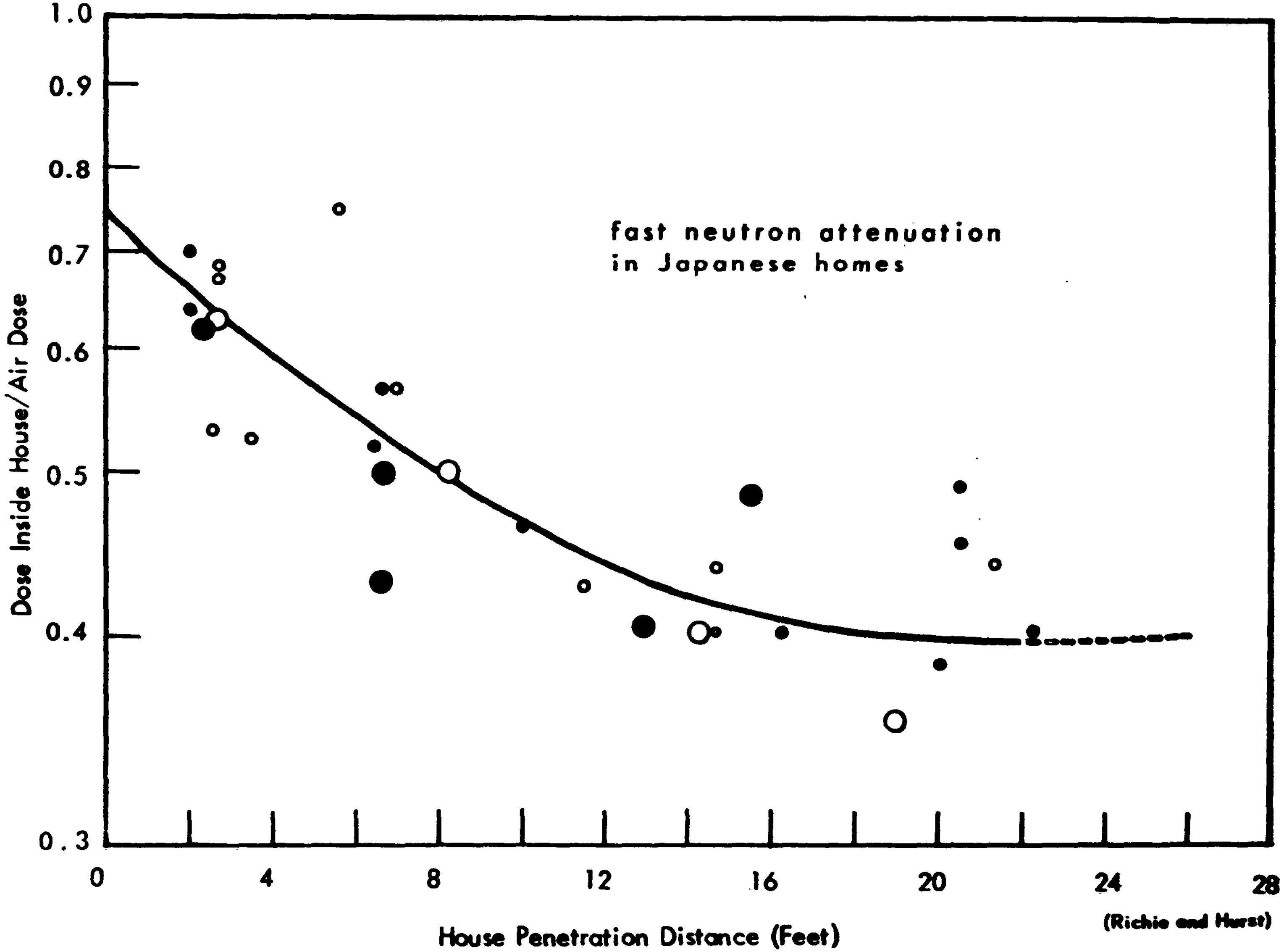


Figure 11. Radiation attenuation - Japanese-type homes - neutrons

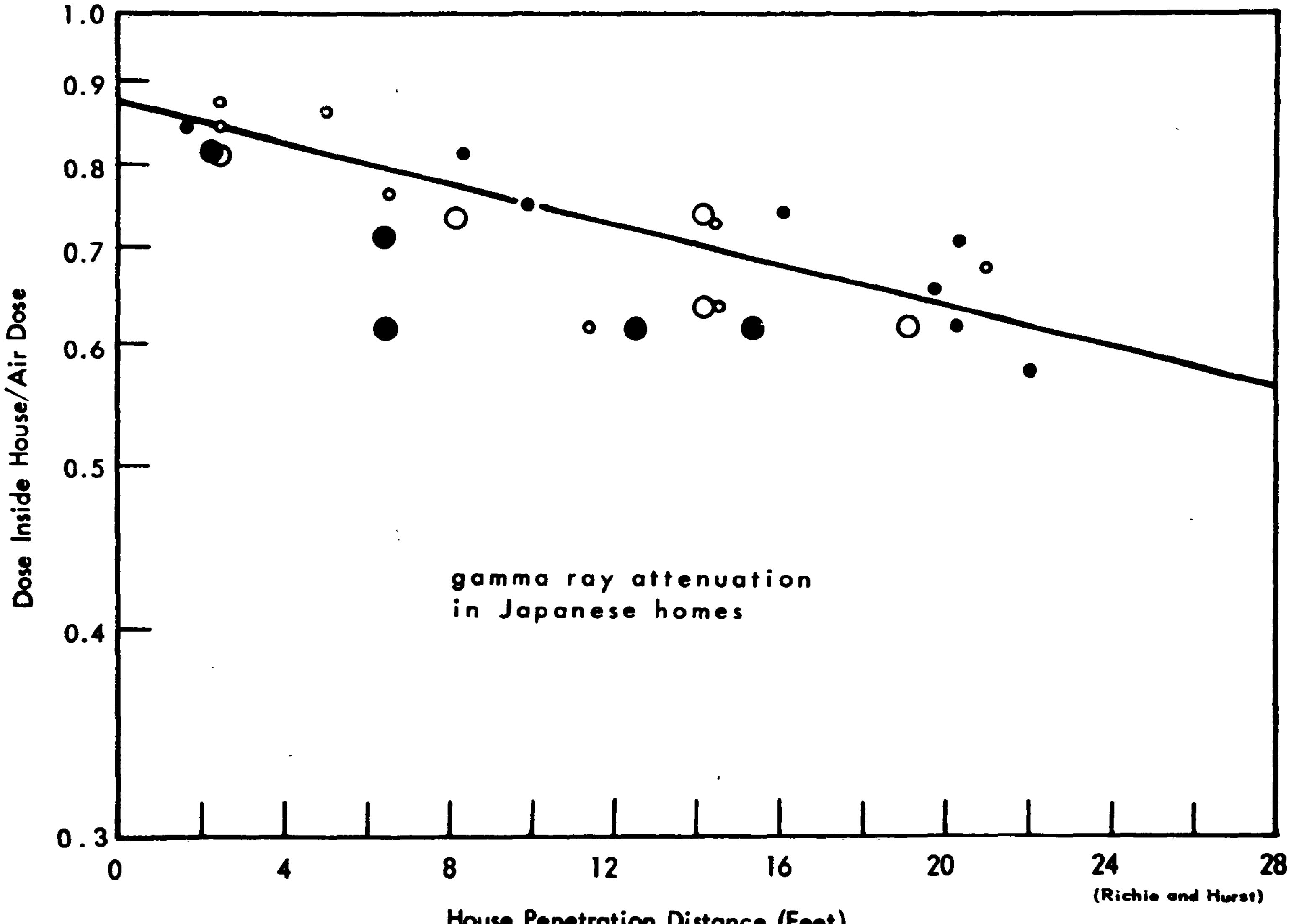


Figure 12. Radiation attenuation - Japanese-type homes - gamma rays

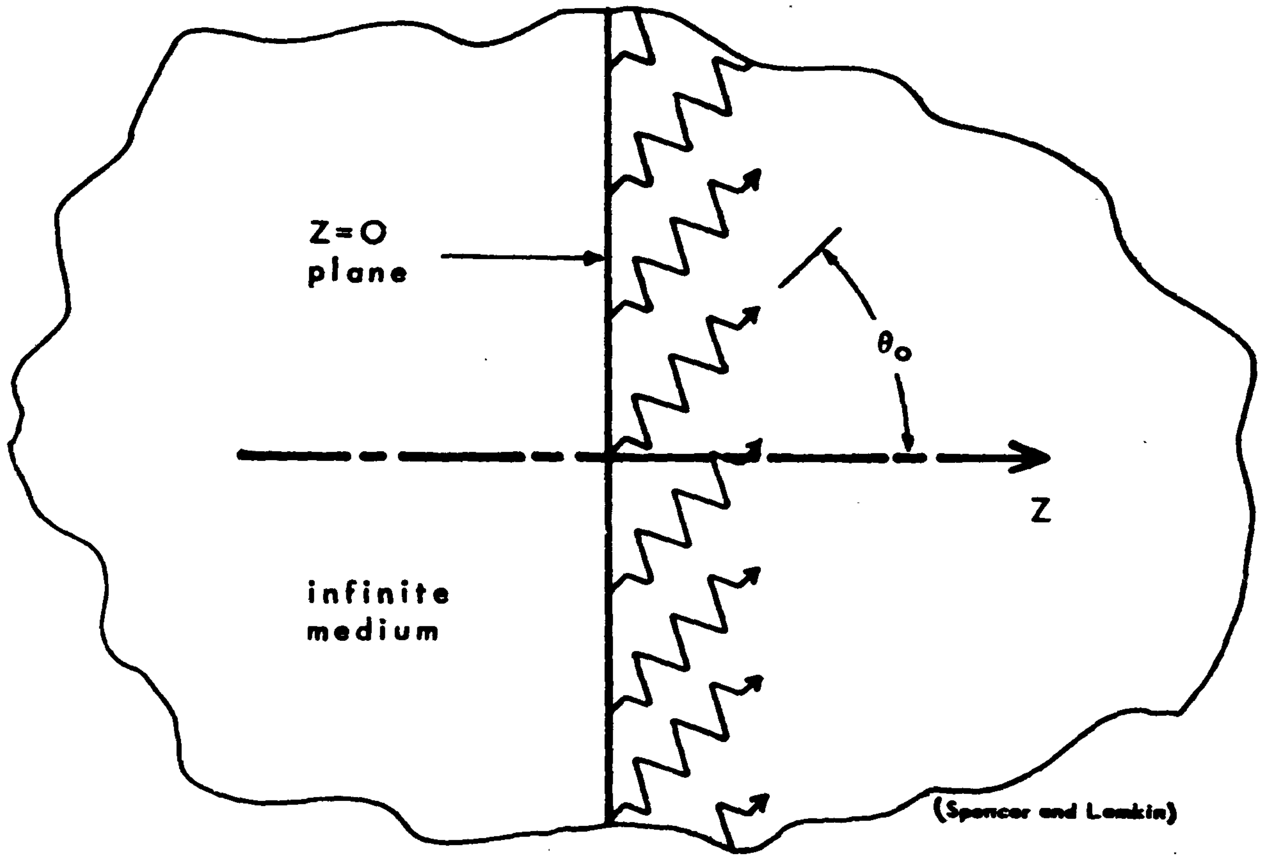


Figure 13. Parallel, broad-beam radiation at oblique incidence on the reference plane

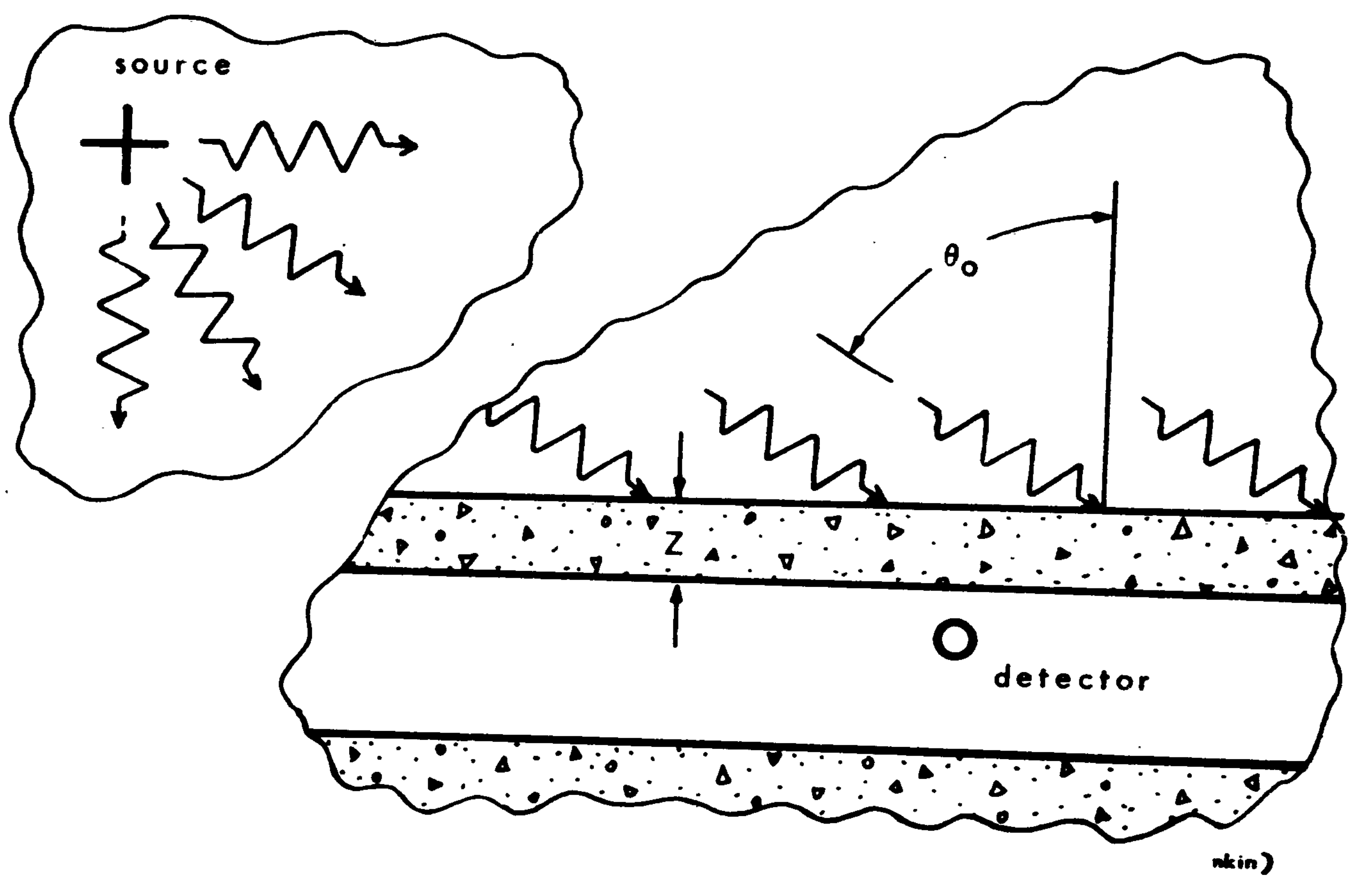


Figure 14. Idealized shielding situation studied by analysis of problem depicted in Figure 13

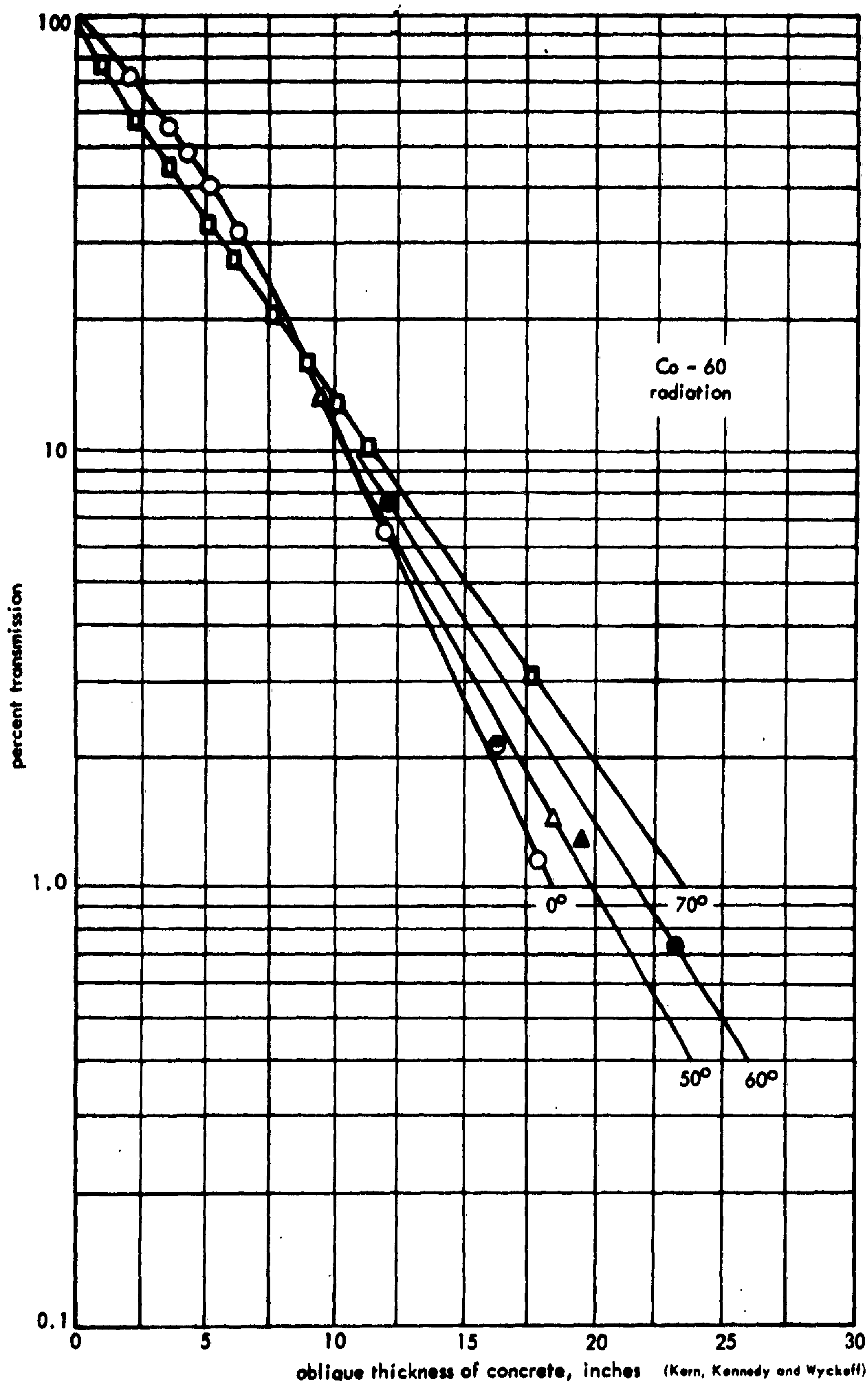


Figure 15. Parallel, broad-beam attenuation in thick slab shields of concrete - oblique incidence

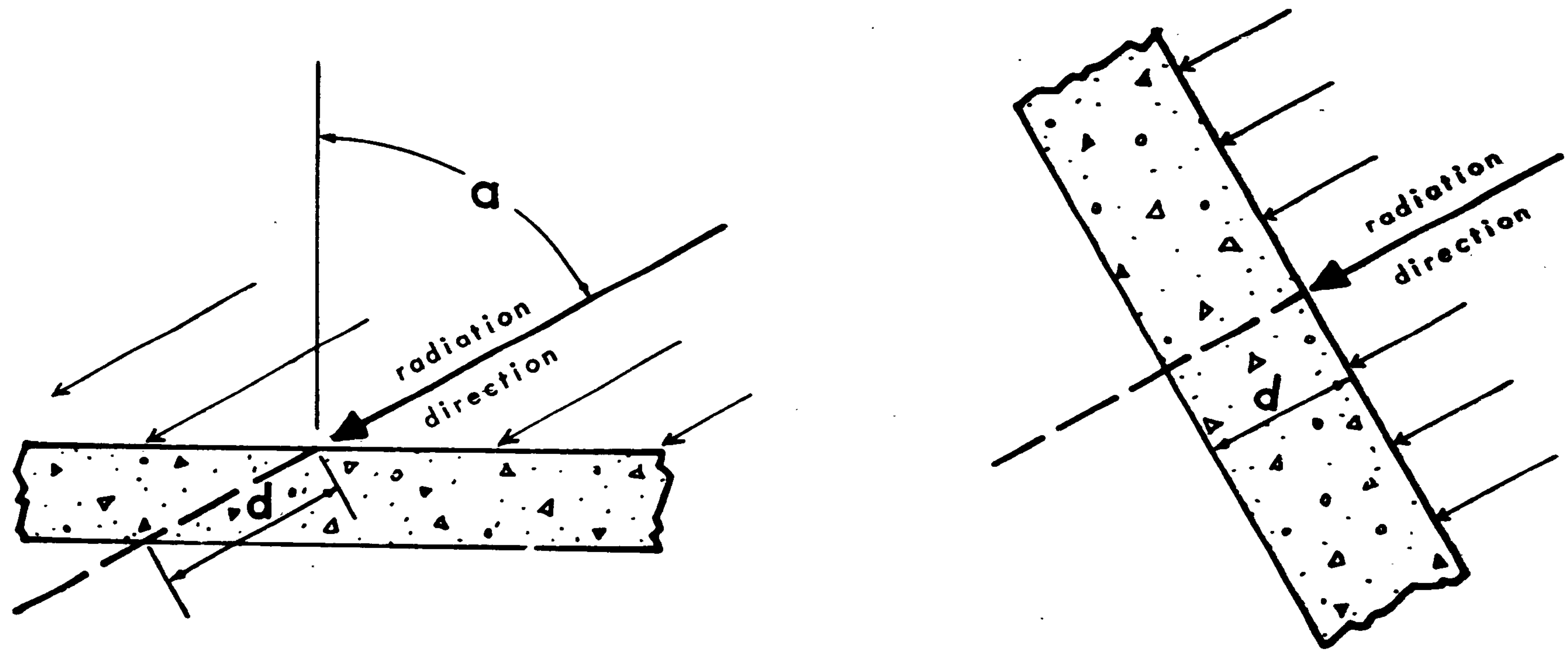
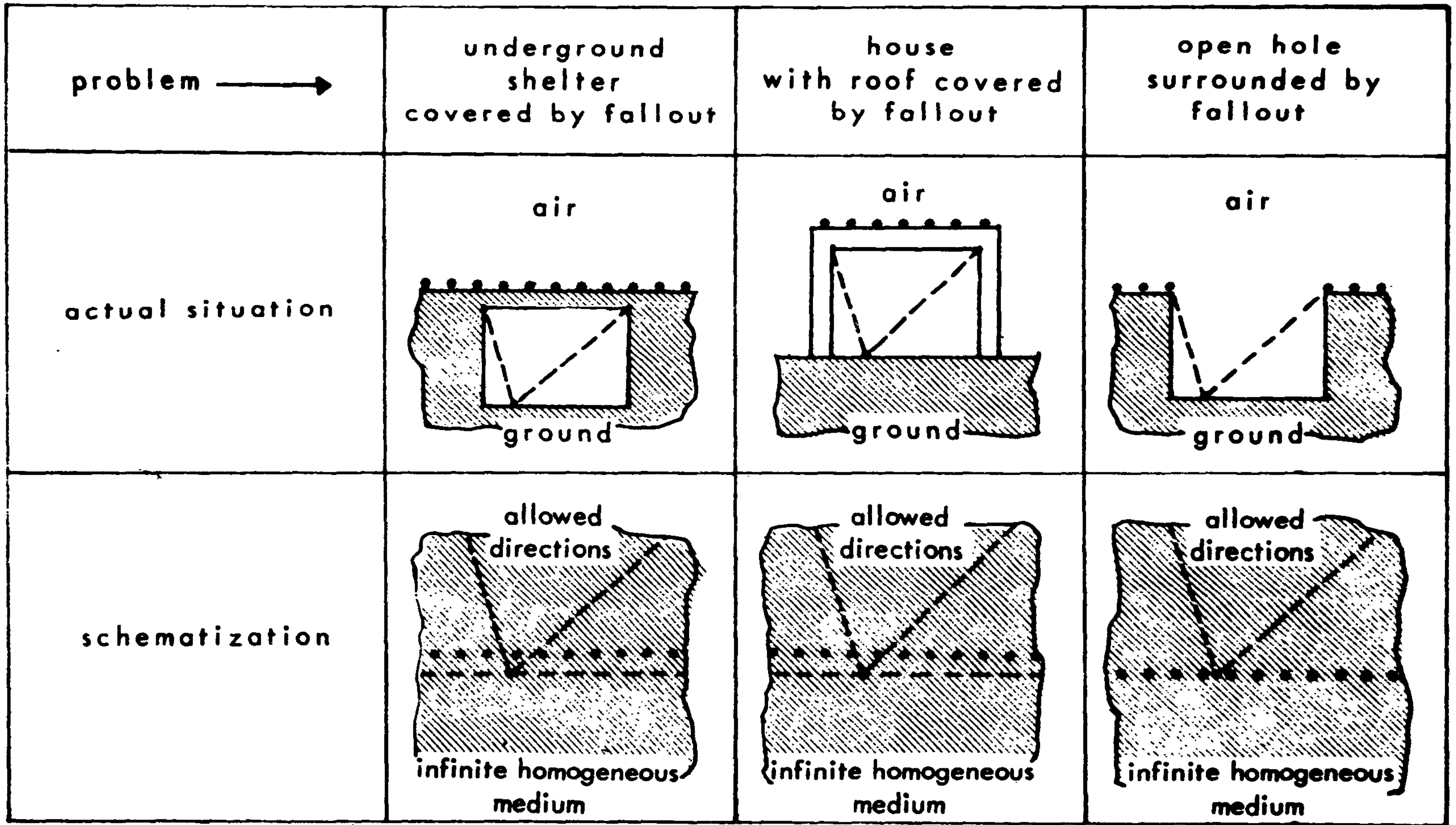


Figure 16. Elementary approach to shielding equivalence for oblique, broad-beam radiation



(Berger and Lamkin)

Figure 17. Schematization of practical shielding situations, to permit analysis

• • • • • • isotropic source
• detector

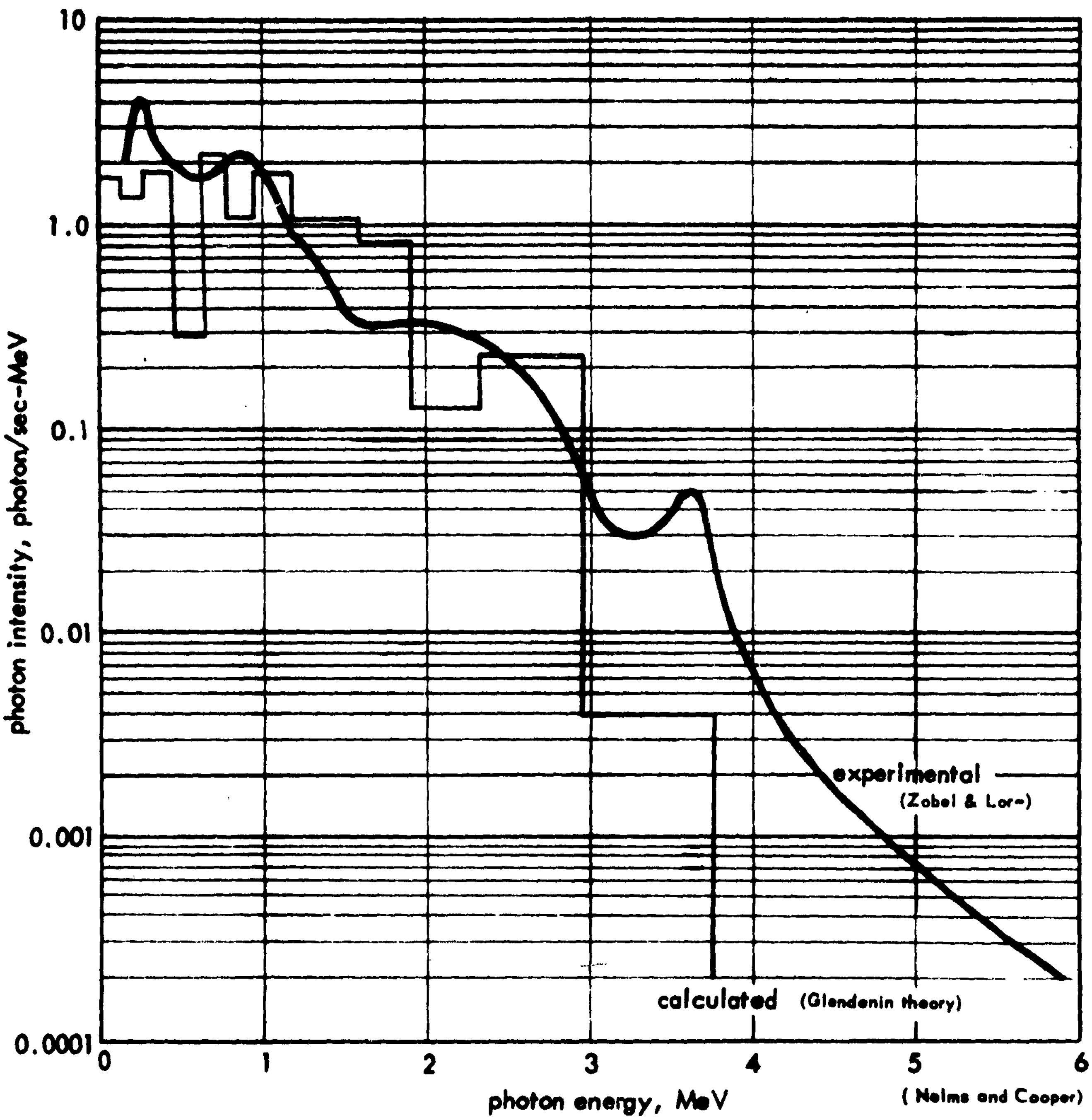


Figure 18. Energy distribution of gamma ray photons from fallout, at about one-half hour after bomb burst.

Figure 19. Experimental set-up to study effect of density changes across interface in shielding material

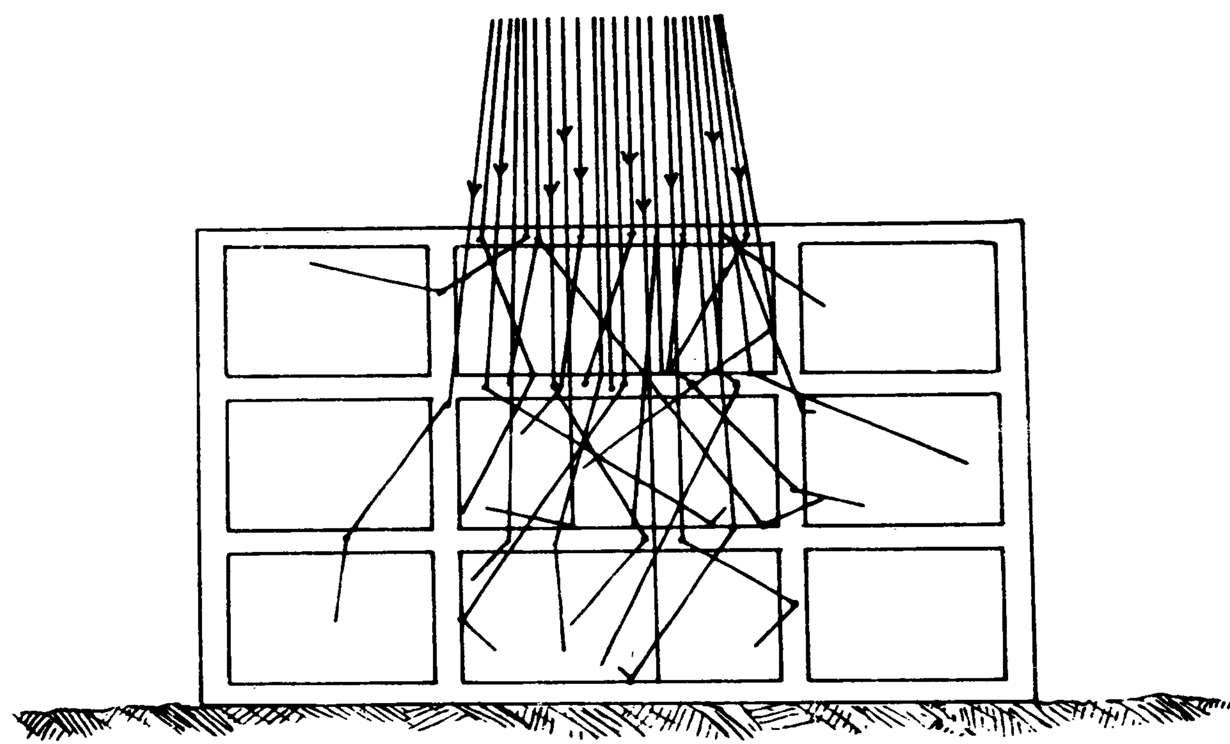


Figure 20. Effect of building compartmentation on radiation

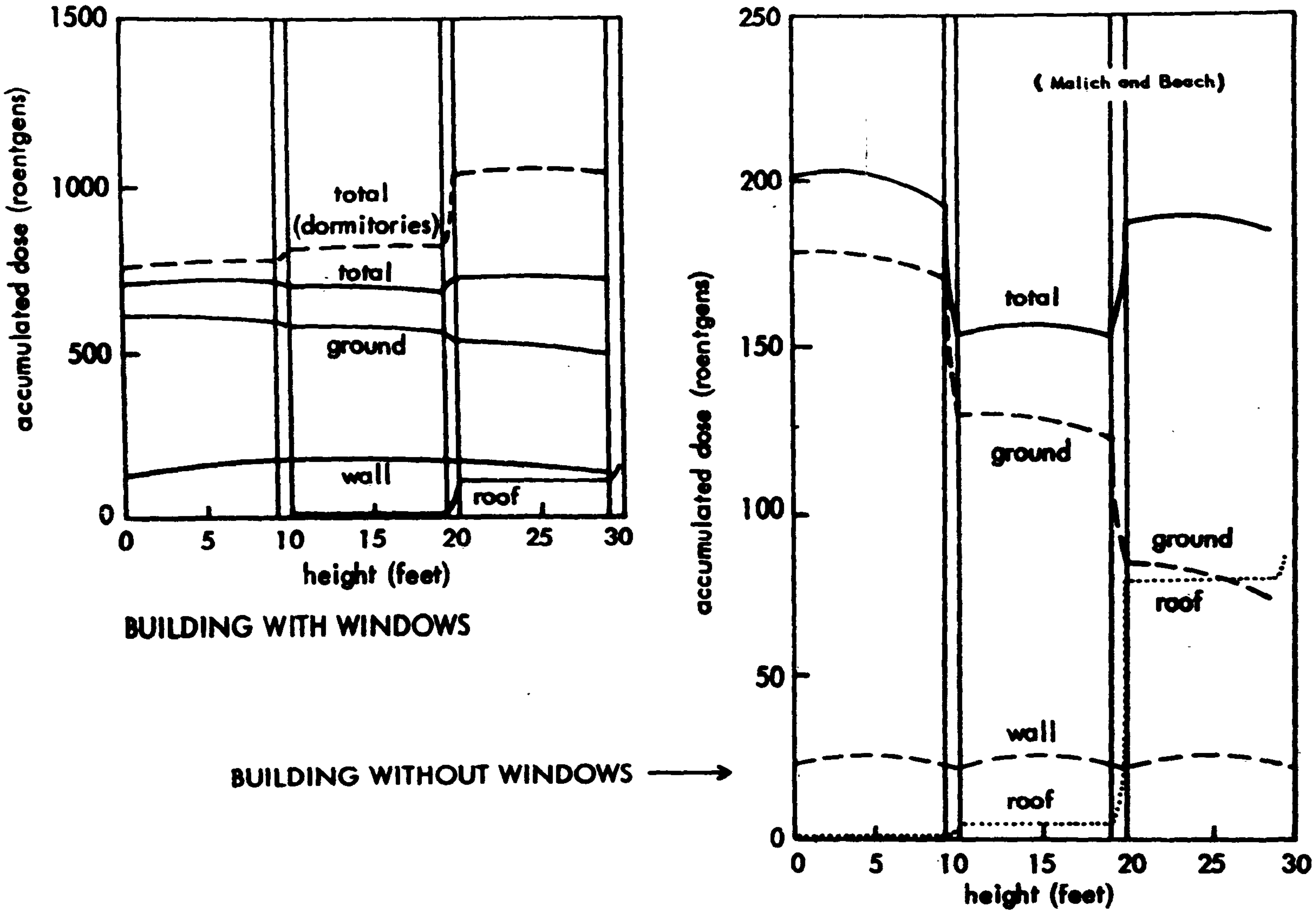


Figure 21. Attenuation of Navy barracks building for fallout gamma radiation

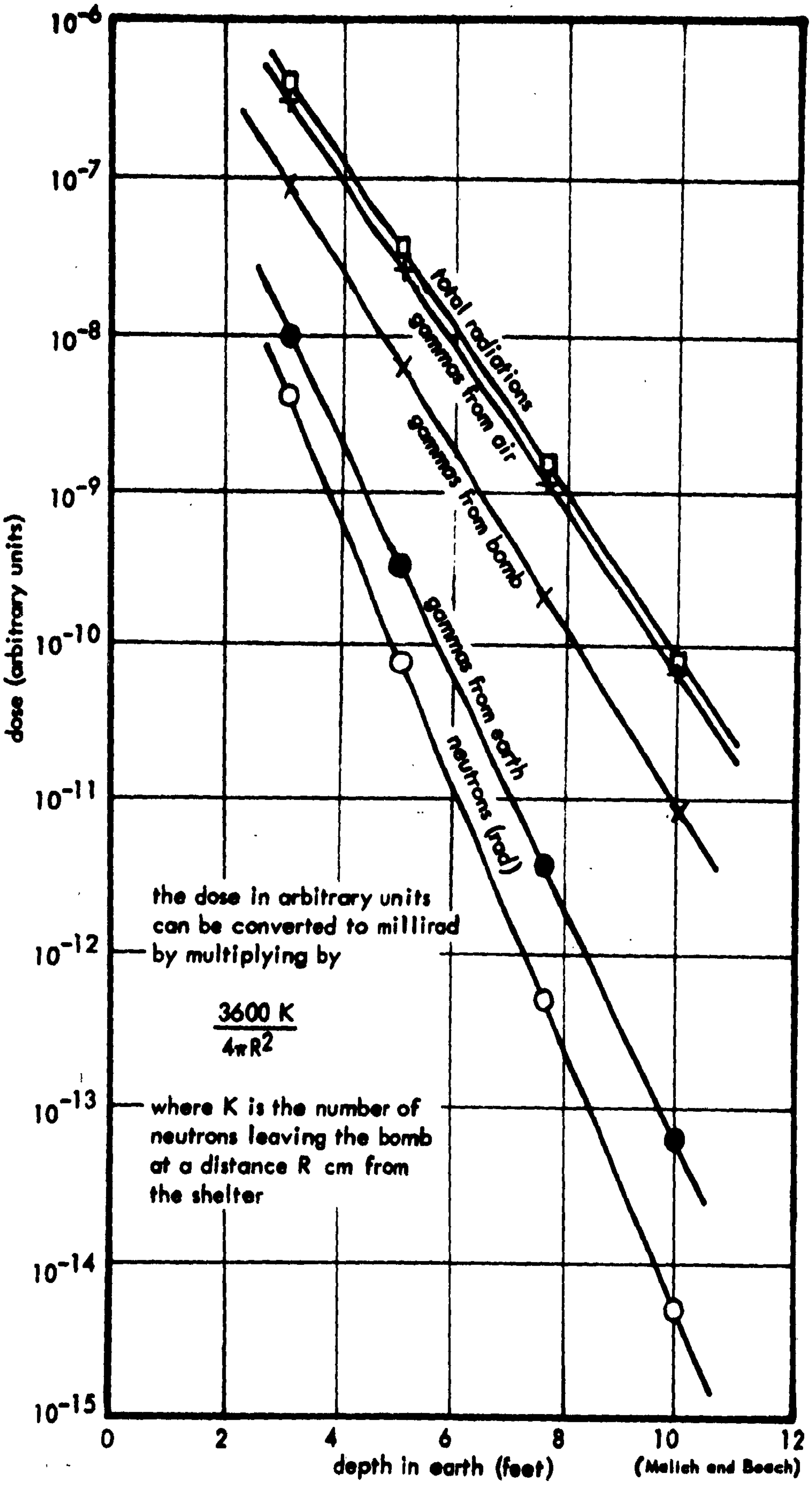


Figure 22. Attenuation of Navy underground shelters for initial bomb radiation - NRL

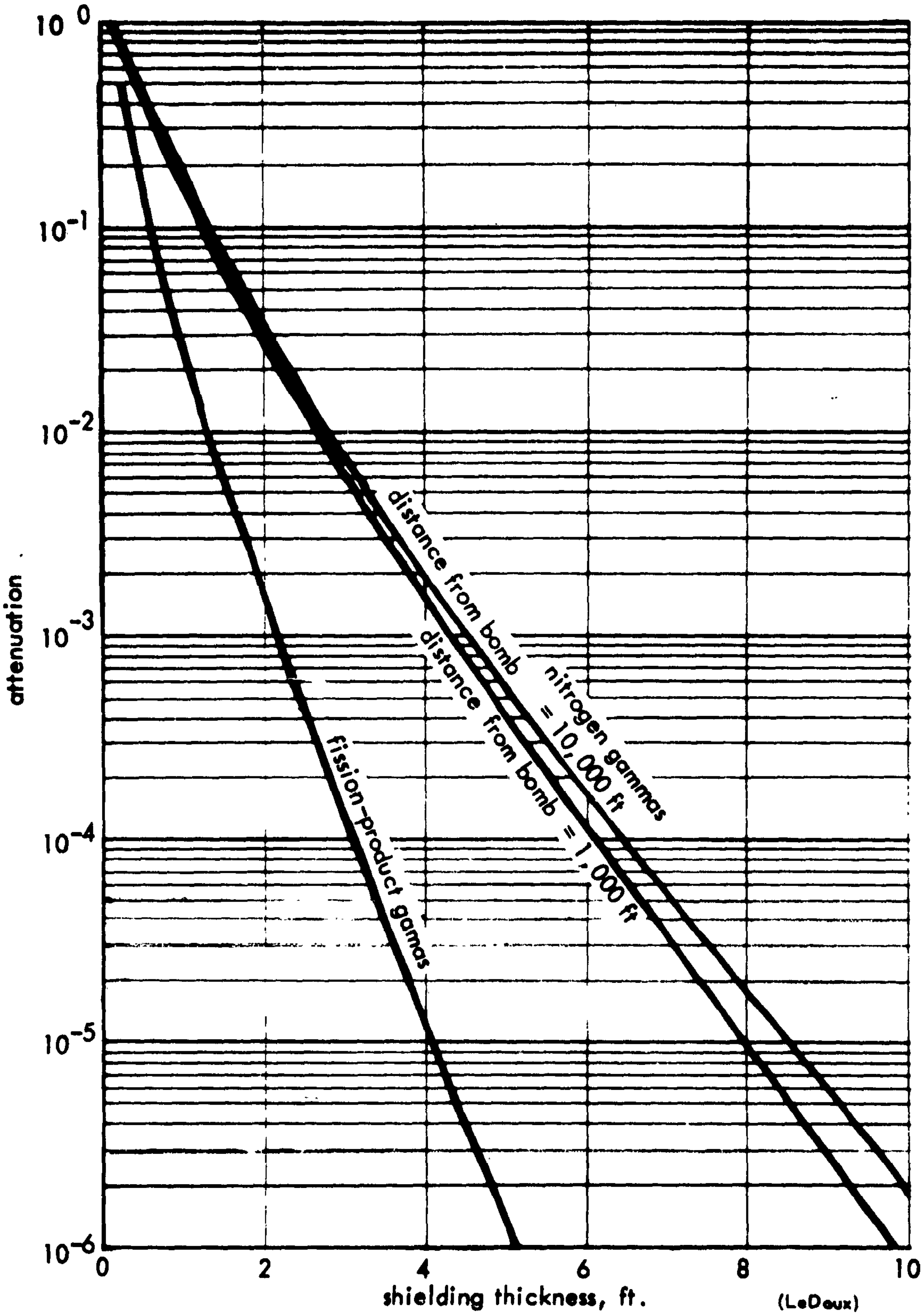


Figure 23. Attenuation of Navy underground shelters for initial bomb gamma radiation - NCEL

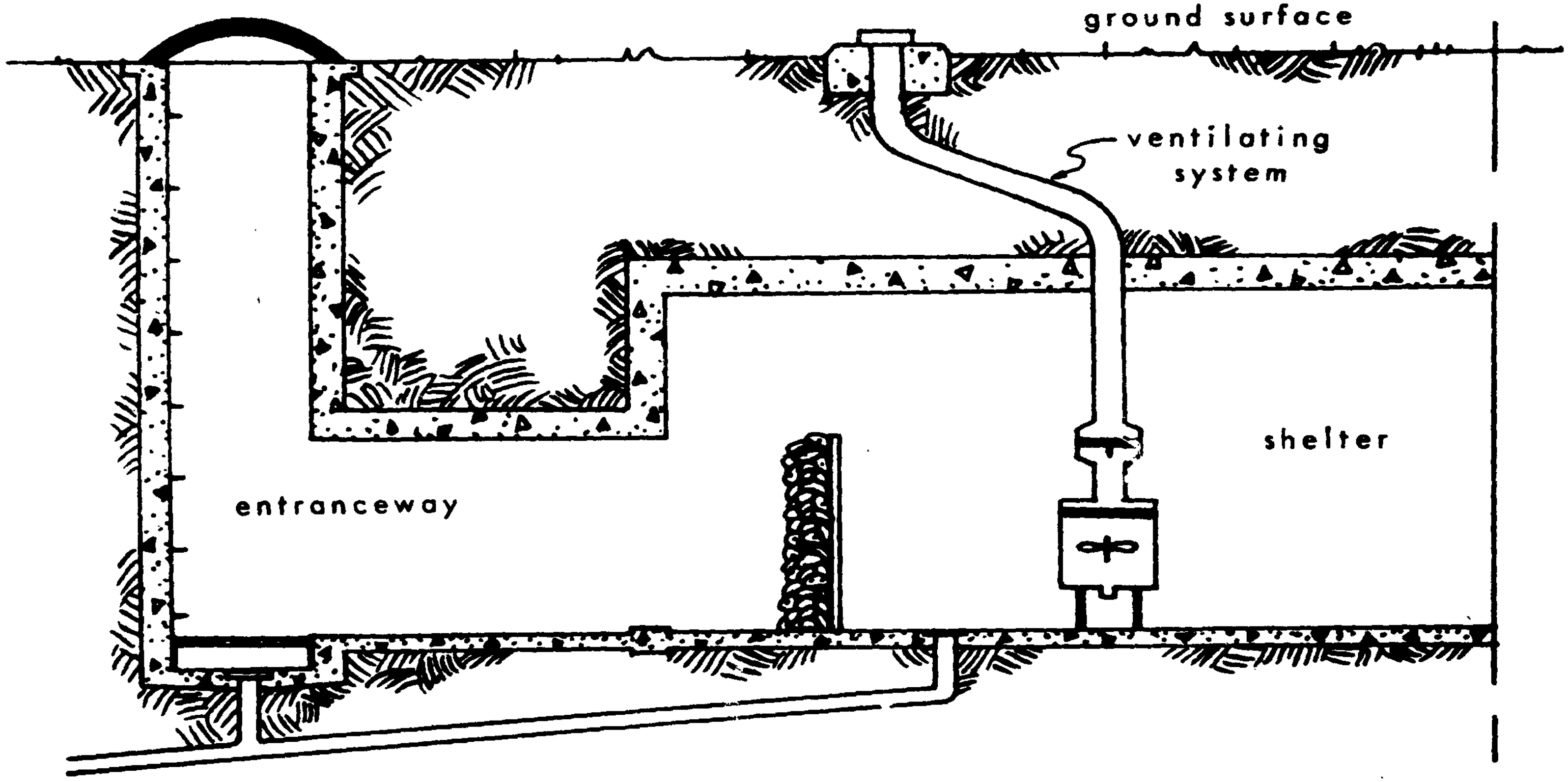


Figure 24. Sketch of part of typical underground shelter

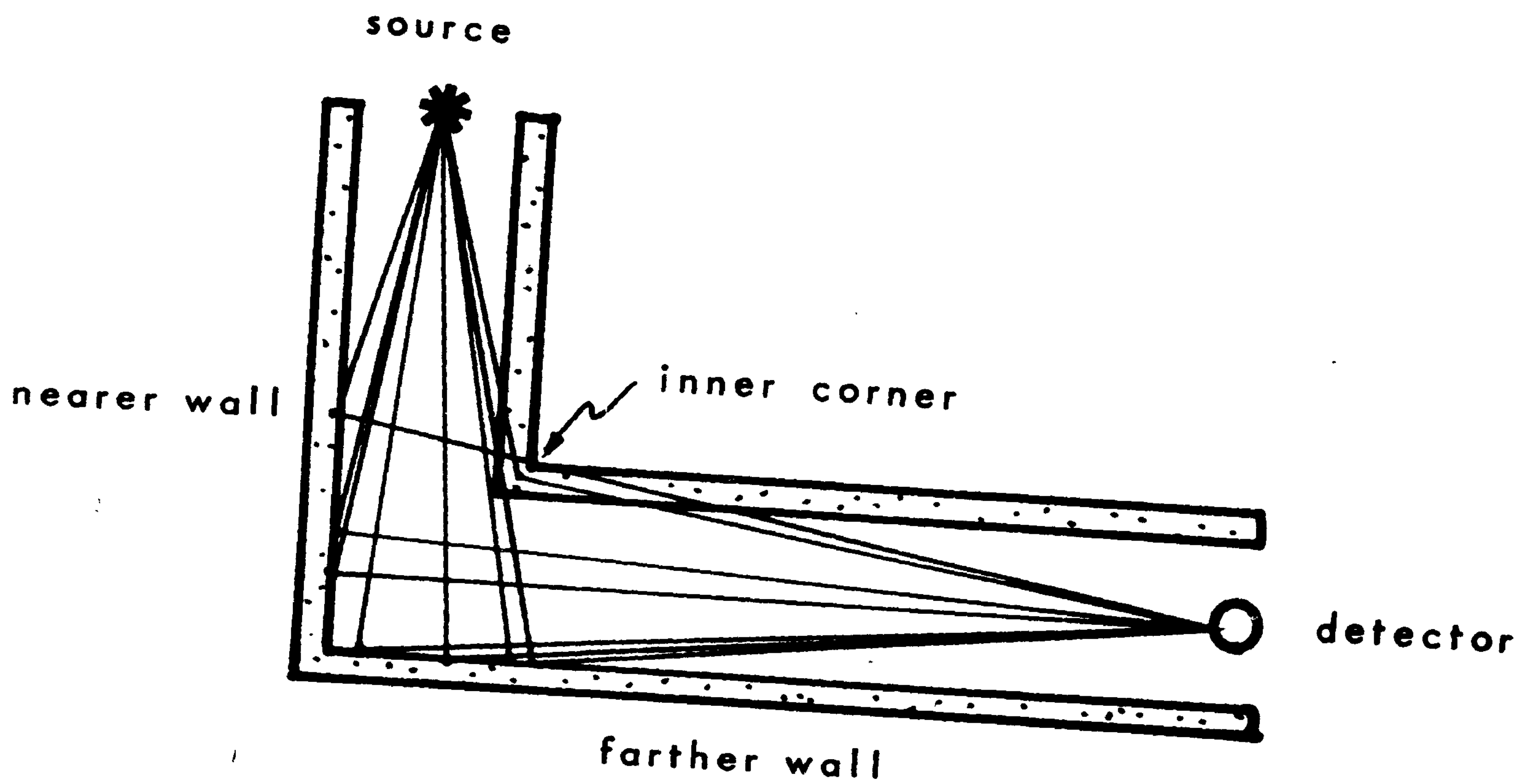


Figure 25. Idealized situation used in study of duct attenuation and "corner" effect

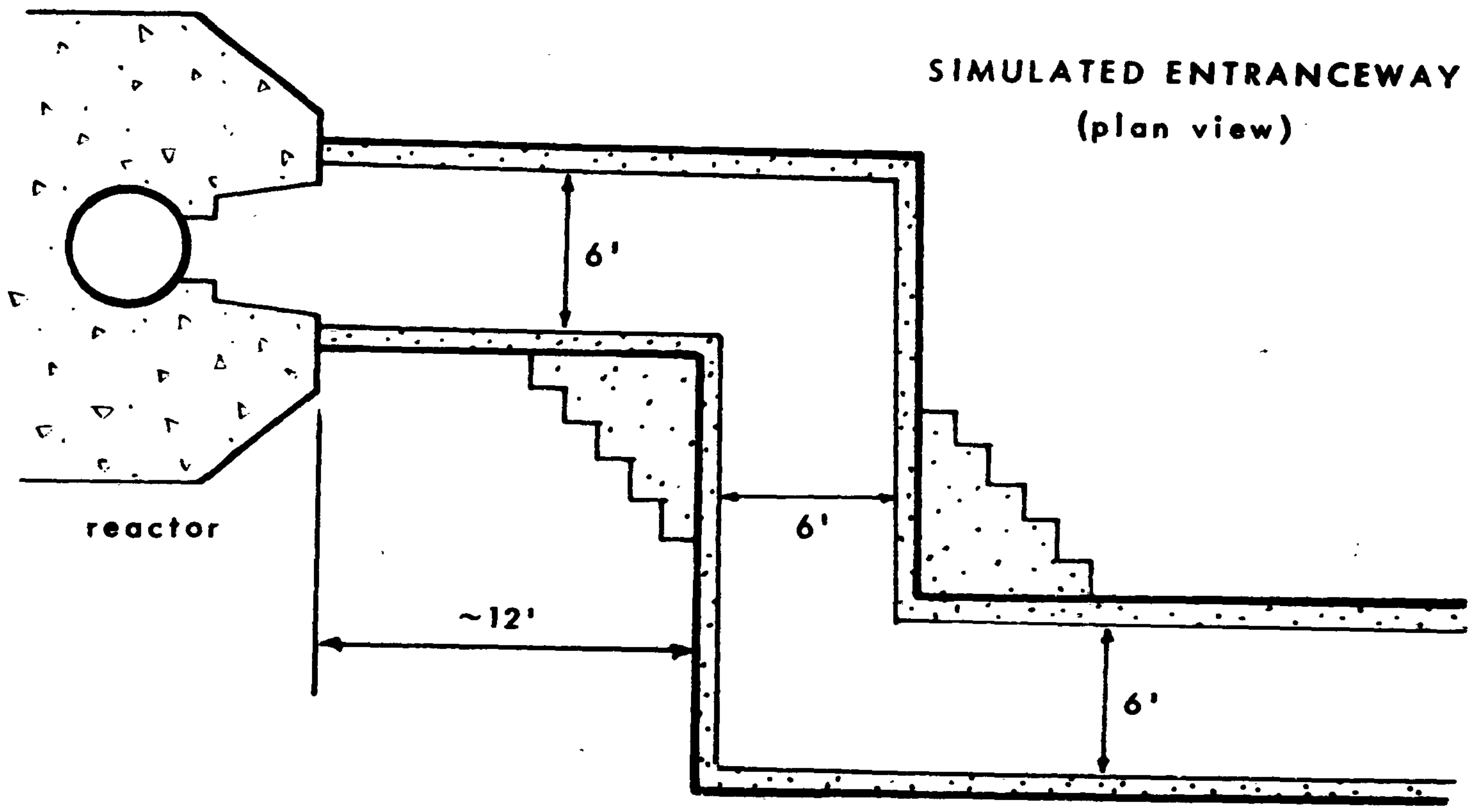


Figure 26. Experimental set-up for study of full-scale entranceway - ARF

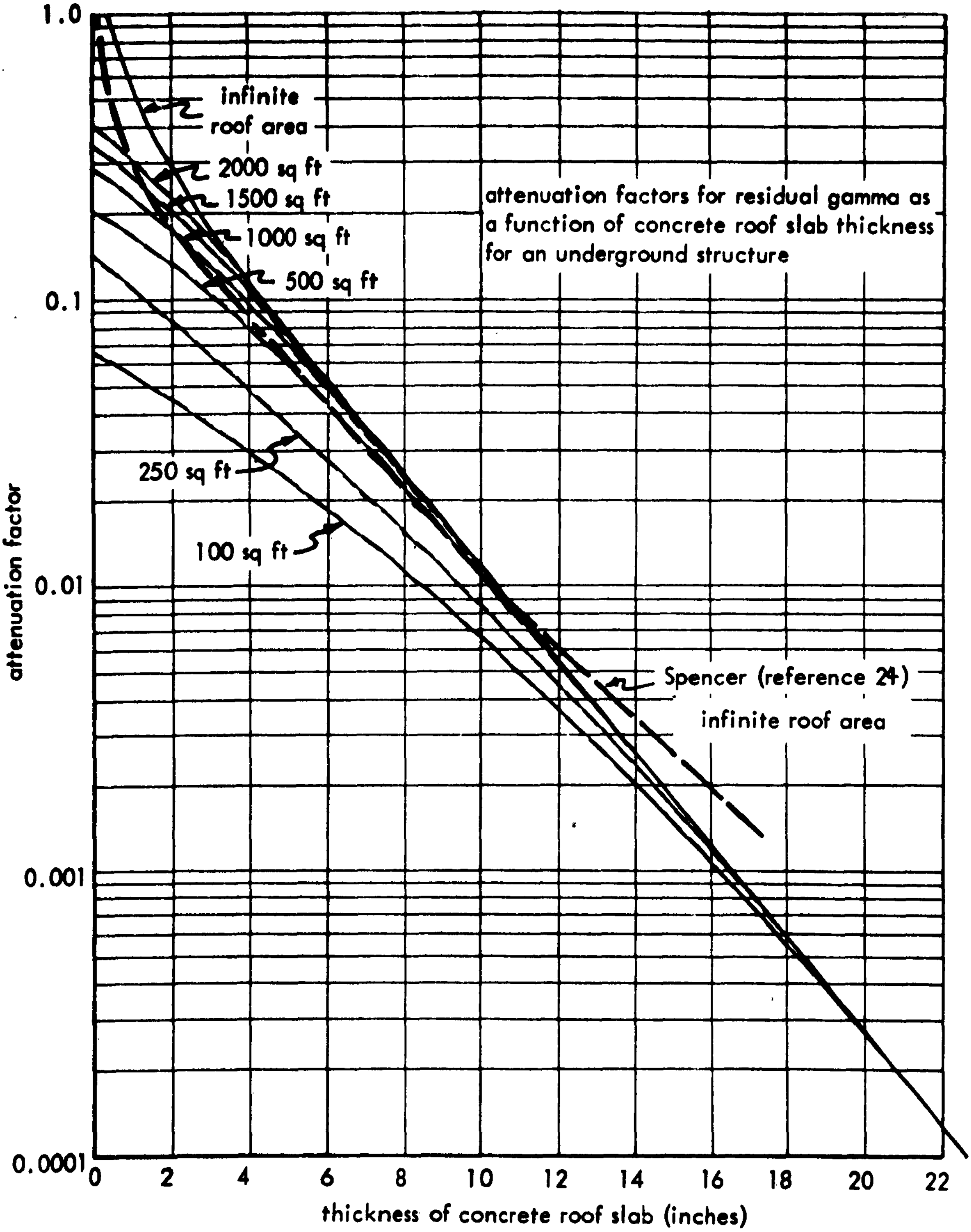


Figure 27. Shielding effectiveness of underground structures of regular shape for fallout radiation

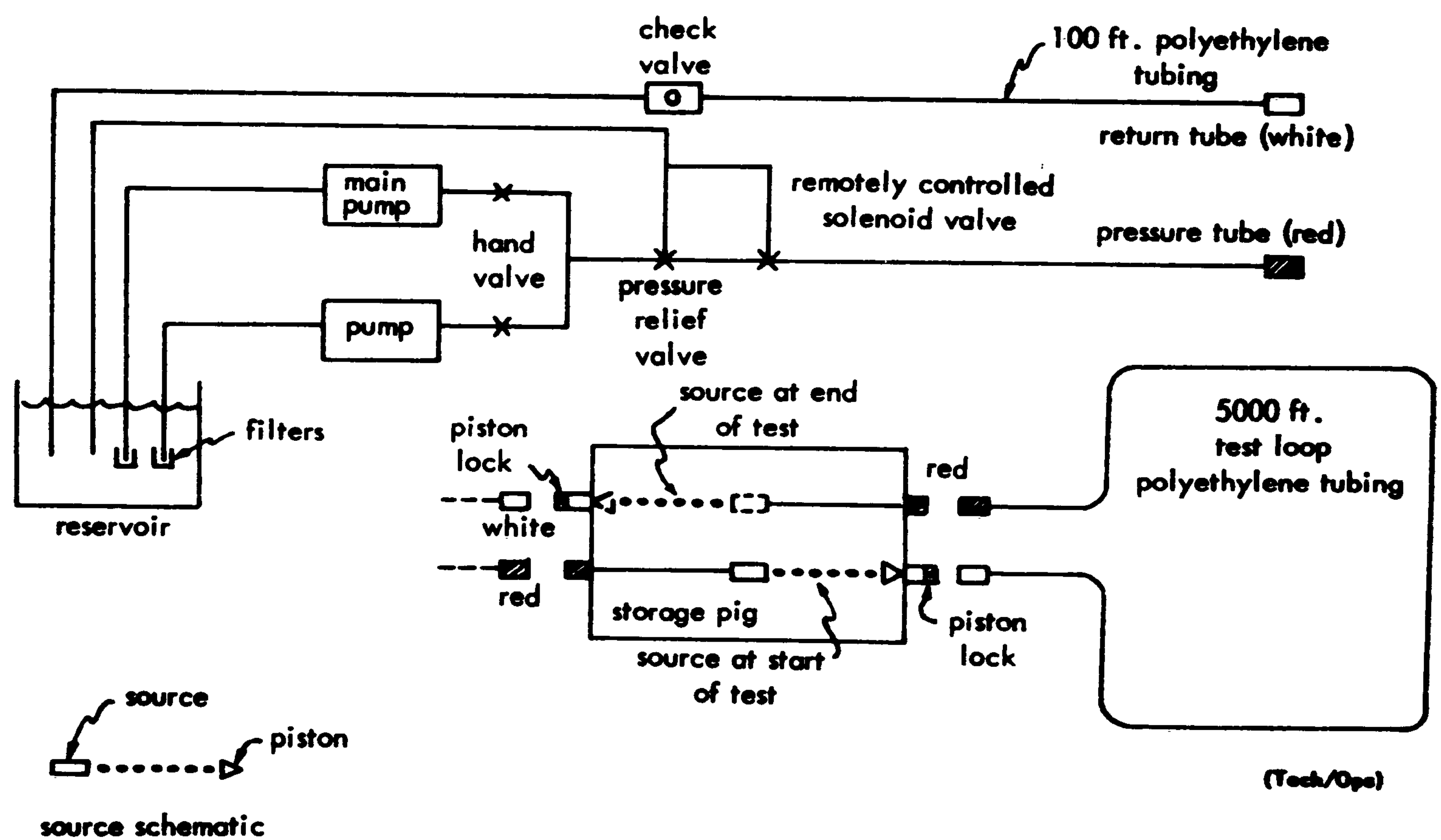


Figure 28. Line diagram of apparatus for moving radioactive source about area to simulate fallout - Tech/Ops